

AL/CF-TR-1996-0026



**ADVANCED DEVELOPMENT OF NEW ACTUATORS  
FOR HUMAN SENSORY FEEDBACK**

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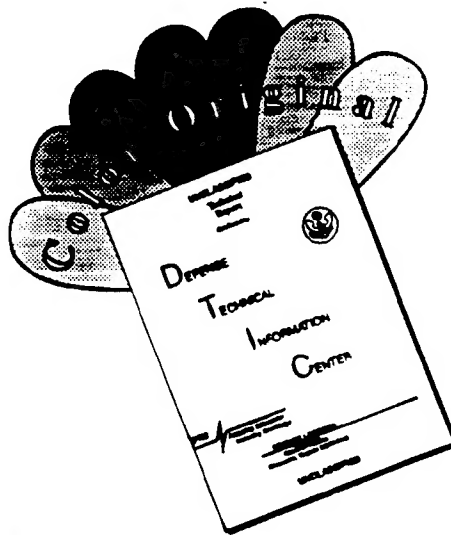
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13. ABSTRACT (Maximum 200 words) The objective of this SBIR Phase II project was to develop a small magnetostrictive actuator using Terfenol-D. The device was configured to be applicable to dexterous force feedback. Several device configurations were studied. The final Terfenol-D actuator was configured as an inchworm motor. The device can be adjusted to be fully back-drivable. The motor is small (approx. 3cc), light weight (16 grams), and provides forces (10N max) and velocities (14.5 cm/sec max) appropriate to the task of dexterous force feedback. The motor driven at 5 KHz could be used for both force and tactile feedback. The device was shown to be highly controllable by means of pulse-width modulation and current control methods. The device was demonstrated in several modes: constant force on a stationary object, arbitrary force output, constant force on an arbitrarily moving object and arbitrary velocity control. Exoskeleton issues were explored and the motors are integrated into a rudimentary three degree of freedom, force-feedback finger with adjustable virtual axis joints. Each joint has a magnetostrictive motor, angle sensor and load cell. Electronic boards are controlled by simple software to demonstrate the motors and the force-feedback exoskeletal finger.				
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# **Advanced Development of New Actuators for Human Sensory Feedback**

## **SBIR Phase II - Final Report**



### **◆ Introduction & Background ◆**

The purpose of this Phase II SBIR contract was to develop new actuator mechanisms, utilizing a magnetostrictive material (Terfenol-D). The new actuators are applied to human sensory feedback in the form of dexterous exoskeletal control for telerobotics or virtual reality applications. While the new motor technology is still in its infancy we have demonstrated that the new motors can be made fast, strong, small and have a bandwidth high enough to model both force and tactile response with a single actuator within a reasonable human range.

Terfenol-D is a magnetostrictive material developed by scientists at the Naval Ordnance Laboratory, (now the Naval Surface Weapons Center), in Silver Spring, Maryland, and the Ames Laboratory, (located at Iowa State), of the U.S. Department of Energy. It is an alloy of terbium, dysprosium, and iron. The name "Terfenol-D" is representative of the composition of the material and the original name for the Navy laboratory where the work was begun. The breakdown is as follows[Butler]: *Ter* (terbium), *fe* (iron), *nol* (Naval Ordnance Laboratory), *D* (dysprosium). Magnetostrictive materials are materials which change shape when exposed to magnetic fields. Magnetostrictive materials have been available for over a century since their discovery by James Joule in 1842. They came into common use in the 1950's with the use of nickel-based alloys for ultrasonic applications. These alloys were limited to strains (change in length) on the order of 50 parts per million (ppm). The discovery of piezoceramics improved this with strains of approximately 250 ppm. Discovery of Terfenol-D, a relatively new magnetostrictive material, improved on the magnitude of the achievable strains by a factor of at least 40 times or an order of magnitude greater than piezoceramics such as lead titanate zirconate (LTZ). Thus Terfenol-D has also been referred to as a giant magnetostrictive material.

Actuators based on Terfenol-D have been shown to transmit large amounts of energy in a small volume and are highly efficient. The Terfenol-D actuators, compared to piezoceramics, can operate at low voltages and require relatively low intensity magnetic fields. The new alloy is being applied to many applications which have been previously accomplished by piezoceramics or traditional electric motors. The Terfenol-D material demonstrates a high Young's modulus



and can withstand compressive stresses on the order of to 780 N/mm<sup>2</sup>. The material has a rapid response time. Devices have been demonstrated operational frequencies over 40 KHz. This is a great advantage over shape memory alloys such as Nitinol. The functional characteristics of the Terfenol-D magnetostrictive technology provides the basis for innovative new actuator designs of interest in this proposal. Other systems have benefited from the use of the Terfenol-D material and include active vibration suppression systems in industrial and in military and space environments. New actuators based on the new material have been proposed and are under investigation for many varied applications such as; servovalves, sonar, machine tool chucks, linear motors, rotary motors, hydraulic pistons, active vibration control, fuel injection, smart control surfaces and structures for spacecraft, aircraft and marine vehicles [Fanson, Wada, Takahara, Goodfriend].

Actuators made from Terfenol-D have been used for micro-actuators with high precision and micro displacements, and as acoustical drivers. Schemes using magnetostrictive materials as macro-actuators normally involve designs that rectify the tiny oscillatory motions of the material to produce large displacements. In general, magnetostrictive linear motors take the form of inchworm motors. In a simple form, an inchworm motor consists of three actuators, namely: two brake actuators and one push actuator. Linear motion is obtained by activating the three actuators in a phased cyclic manner.

The primary objective of this research was to develop an actuator that could be used as a small, linear motor in dexterous exoskeletal feedback. The motor concept in mind was an *inchworm* motor. An inchworm motor generally utilizes both active and passive actuation. One such configuration consists of two brakes and a mover. One brake locks the motor position onto a shaft and the mover then advances (stretches) the motor forward. While the motor is stretched forward, the other brake clamps down on the shaft and the first brake releases. The process is then repeated many times over. In this manner the motor will *inch* forward in a method somewhat similar to an inchworm in nature.

The integration of human control and robots has a number of demonstrated advantages. For example combining cognitive capabilities of the human with the strength and durability of robots facilitates remote operation in hazardous and lethal condition. Significant effort has been expended in developing robotic end effectors, sensors and exoskeleton to control the motions of the robotic arms and hands. Human size robotic hands have been developed which can effect fine manipulations. While advances are impressive much room for improvement is available. Concepts for force feedback are not new but the implementation of actual physical systems is definitely an area which needs continued development. For intuitive control and fine manipulation, high capability, small, light weight exoskeletons and or virtual objects with force feedback actuators are needed. The development of anthropomorphic dexterous force feedback systems has naturally lagged behind the development of anthropomorphic robotic hands. And both technologies need better actuators. In addition to the application for robotic control the explosion of virtual reality software has increased need for realistic force feedback. Demand for

dexterous force feedback systems is no longer limited by the lack of a good slave robotic hand since many software applications are begging for a good anthropomorphic tactile and force feedback interfaces.

The quality of actuation systems has been recognized as the bottleneck of control in dexterous telemanipulation where force feedback is required [Burdea]. The three types of actuators typically used include pneumatic, electromagnetic and hydraulic. Each has its own set of merits and limitations. Pneumatic actuators can be compact and lightweight, but possess relatively low bandwidth properties, low actuation stiffness and low power production capabilities. Electromagnetic actuators, on the other hand, have good stiffness properties, and high bandwidth, but are relatively sizable and heavy. Hydraulic actuators have traditionally been considered the most appropriate, because their properties lie somewhere between the other two systems. If the size and weight limitations of electromagnetic actuators can be overcome, then their other properties will make them the obvious choice.

As telerobotic and virtual reality systems gain popularity in industrial and technical settings, the need for improvements in the science of haptic sensing has become increasingly important. Haptic science is composed of two parts: "tactile perception, or the awareness of stimulation at the skin, and kinesthesia, or the sense of joint positions, movements and torques"[Chang]. Important to this science is the need to improve on commercially available dexterous exoskeletons used to measure motions of the hand and reflect object shape, compliance, impact, contact, sliding, slipping, and kinematic constraints. This actuator will eventually be used to provide force feedback in dexterous exoskeletons for use in telerobotics and virtual reality systems.

Virtual reality is defined as a "computer generated immersive environment with which users have real-time, multisensorial interactions"[Burdea]. The participant enters the virtual world by donning special equipment which provides feedback between the two realities. This equipment often includes a visual element whose purpose is to provide the visual perception of the virtual world. Another key piece of hardware used is some type of glove or exoskeleton which measures the movements of the hand and uses this information to control a virtual hand in the virtual world. Since it is this virtual hand that is used to manipulate objects within the virtual world, the dexterous exoskeleton must be able to accurately reflect the virtual forces experienced by the virtual hand. "The key to virtual reality is its interactivity - it's not a place where you go and watch, it's a place where you go to do things" [Delaney]. As virtual reality moves from the games environment to a simulation environment where real objectives are accomplished, the devices used to reflect the virtual forces "must match as many of the kinesthetic ... capabilities of the human hand ... as [the available] technology will allow" [Chang]. The less the wearer of the glove/exoskeleton is physically burdened by the device, the more realistic the virtual experience will be. Bulky and heavy attachments to the hand detract from the experience and contribute to the fatigue felt by the operator over time. Advances are incremental as improvements are made through reductions in size and mass. As the hardware becomes smaller and lighter, the performance of the virtual reality system will improve.

For telerobotics, "future strategies for environmental clean-up and hazardous waste removal will rely primarily on remote manipulation and sensing"[Long]. The integration of human control and robots has demonstrated advantages by combining the cognitive capabilities of the human with the strength and durability of robots. With teleoperation, the human is given the ability to operate real time in lethal and hazardous environments. The operation of telerobotic systems is not unlike the operation of a virtual reality environment. The principal difference is that in virtual reality, the operator interacts with a virtual world, where in teleoperation, the operator is actually controlling a remote device such as a robotic manipulator. Like virtual reality, the teleoperation of multifingered robots also requires the use of a dexterous master or exoskeleton which is a multi-DOF controller and is worn on the operator's hand [Burdea]. As the operator moves his hand, the system monitors the changes in position and orientation and reflects these changes back to the robotic manipulator. Force and tactile information is then fed back into the exoskeletal hand. For reasons similar to those with virtual reality, improvements in the size and mass of the exoskeletal dexterous master would improve overall operator performance.

Force feedback is often separated from tactile feedback which involves the ability to create the sensation of touching textures or distinguishing surfaces. This is due to the fact that, other than the motor discussed in this project, no force actuators were available which provided high frequency tactile forces and bulk forces simultaneously. In a study intended to improve the design of space suit gloves, Chodack and Spampinato reported the results of their "peg-board dexterity test". When four (4) subjects wore gloves, the time it took for these subjects to insert the pegs increased by 80% when compared to using their bare hands. This is an indication of how important force and tactile feedback are to dexterous manipulation. In telerobotics or virtual manipulation, if the operator were able to feel the forces as if he/she were actually present performing the work, productivity would increase.

Why is a better motor or actuator needed? There are many exoskeletal hands now available that provide a type of force feedback to the operator. The technologies used are many and varied and include: pneumatic, hydraulic, cable driven, and electric solutions.

A good reviews of existing devices were prepared by KB Shimoga and Hasser. Shimoga analyzed and compared at least 14 different devices designed for use in the telemanipulation environment. He arrived at six conclusions. They are:

1. Of the fourteen designs discussed [in his review], only six are capable of providing some force feedback.
2. None of the existing hand masters that are capable of finger force feedback are truly isomorphic to the human hand.
3. A few hand masters are portable while most are bulky.
4. An ideal hand master must function well up to at least 10,000 Hz.
5. An ideal hand master should be able to sustain forces of 4-7 Newtons, and exert forces up to 30-50 Newtons for short periods of time.
6. The hand master should have at least ten times the force sensitivity than that of the human hand. Human fingers can sense force steps of about 0.5 Newtons.

Based on the review by Shimoga, the existing force feedback devices are not adequate to provide realistic force reflection. A new device is needed that is small and lightweight, has a high force density, and can operate anywhere from 0 Hz to 10 KHz.

In a small Phase I project to identify the feasibility of Terfenol-D based actuators and motors several first generation concepts were tested. By the end of the Phase I we had demonstrated several working joint brake mechanism for resistive feedback. Two selected brake mechanism were fitted to a simple exoskeletal feedback structure for demonstration purposes. In addition to the brake mechanisms a fully functioning Terfenol-D motor was fabricated and tested. The Terfenol-D inchworm motor had adjustment means on each of the brake and pusher elements. This allowed the motor to be configured from an "always locked" to a "fully back-drivable" configuration. In the fully locked configuration the motor was capable of forces in excess of 50 lbf. The motor was about the size of a cigarette pack. It was operated from 0 to 300 Hz. The Phase I motor was too large for the longer range goal of putting the actuator mechanism directly on the finger joints but went a long way in elucidating the problems that needed to be overcome in the development of the smaller, higher speed devices. From that point a more advanced development project was outlined and resulted in this Phase II project to help direct the technology toward the goal of a small high force, high speed Terfenol-D motor for dexterous exoskeletal feedback.

### ♦ Proposed Phase II Tasks ♦

The following are the technical objectives as outlined in the Phase II proposal:

- ♦ **Task 1. System Review**
- ♦ **Task 2. Resistive Actuator Development**
- ♦ **Task 3. Linear Motor Development**
- ♦ **Task 4. Application Simulation**
- ♦ **Task 5. Documentation**

Since the use of Terfenol-D in motors is a relatively new effort the developments in this project were of a necessity iterative. In this report we briefly report on the efforts undertaken under each of the five project task but do not attempt to describe all the iterations and small lessons learned in detail. Actual progress was achieved during the course of the project in an iterative and parallel manner. This final report reviews the progress by the task (as noted above) with no particular effort to show chronology.

## ♦ Phase II Progress ♦

### *Progress - Task 1. System Review.*

In this project the "system" includes the human hand, fingers, finger joints, brake actuators, pusher actuators, inchworm force actuators, angle sensing, force sensing, exoskeletal structure, electrical controllers, computer, software and ergonomic issues. Each of these elements also have subsystems such as solenoid coils, Terfenol-D, etc.,. Each of which had to be studied and developed in order to complete the overall goal. The nature or of the project and its funding limitations sculpted the effort and the overall scope. The state of the art for Terfenol-D motors and anthropomorphic dexterous force feedback both show great promise but the technologies are still in their infancy. Therefore a significant portion of the project involved the study of both telerobotic and magnetostrictive technologies in an effort to establish resonable goals and requirements for design purposes. The telerobotic review targeted operation requirements as it related to dexterous force feedback. In the review of Task 1 in the project we report the ergonomic, physiological issues and then will detail design solutions under review of Task 4.

### *Dexterous Biomechanical Requirements.*

The project began by establishing requirements of the exoskeletal hand interface. The hand related parameters studied were:

- ♦ Size
- ♦ Axis of joint rotation
- ♦ Range of joint motion
- ♦ Finger forces

### *Hand Sizing*

The following data are averages for adult finger bone lengths (Poznanski, 1984). The sizes have been input into a generalized computer model of the hand (Fig. 1 and Fig. 2) in order to study relationships between the joint centers of rotation, segment lengths and the exoskeleton framework.

SEGMENT	#	MALE mm/std dev	FEMALE mm/std dev
Distal	5	18.7/1.3	16.2/1.2
	4	20.5/1.2	18.0/1.3
	3	20.1/1.2	17.7/1.3
	2	18.8/1.4	16.6/1.3
	1	25.2/1.4	22.1/1.6
Middle	5	21.6/1.6	18.7/1.7

	4	29.6/1.6	26.4/1.7
	3	31.1/1.8	27.9/1.7
	2	26.1/1.6	23.2/1.6
Proximal	5	36.3/2.0	32.5/1.9
	4	45.5/2.3	40.8/2.4
	3	48.5/2.6	44.0/2.3
	2	43.7/2.2	40.0/2.3
	1	35.0/1.9	31.4/2.0
Metacarpal	5	58.0/3.0	51.9/3.6
	4	62.1/3.5	56.0/3.5
	3	69.0/3.8	62.6/4.0
	2	73.7/3.8	66.9/4.3
	1	49.6/2.9	44.2/2.6

These sizes represent a sample size of 78 adults of unknown ethnic background, as measured from radiologic studies. Some variability has been reported in the literature in conjunction with ethnicity, but will be ignored at this iteration.

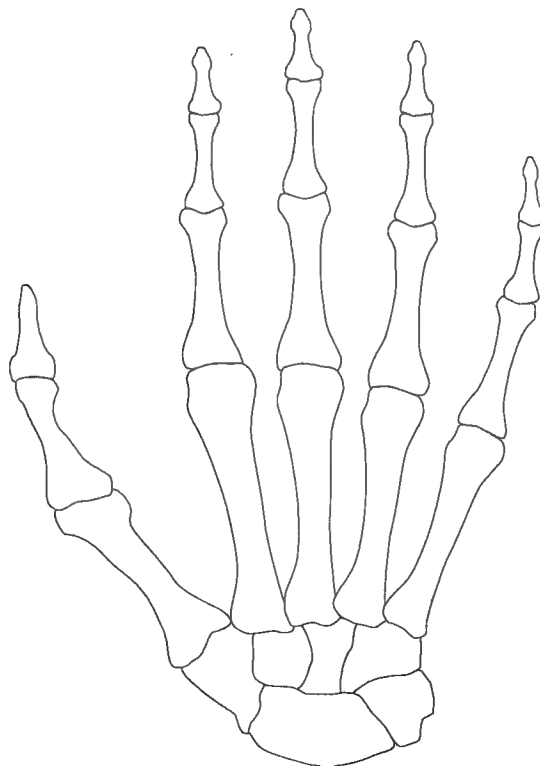


Figure 1.

Data regarding segment length variation, as well as center of rotation locations for the hand joints, have been shown to be linear with respect to hand size (Buchholz, 1992). The variability of the dimensions of the middle phalangeal segment is of particular importance to this study, since a fixed length rigid glove master may be sufficient to cover the majority of the population at that segment if the variance is small enough. The standard deviation of segment size at that level is between 1.6 mm and 1.8 mm for men and women.

Middle phalangeal segment length can be determined from hand size (Buchholz 1992):

Little finger (#5):  $0.117 * \text{hand length}$   
 Ring finger (#4):  $0.165 * \text{hand length}$   
 Middle finger (#3):  $0.170 * \text{hand length}$   
 Index finger (#2):  $0.143 * \text{hand length}$

Percentile hand sizes have been documented from 4000 male air force personnel (Hertzberg, 1959).

<i>PERCENTILE</i>	1	5	50	95	99
Hand Length (in)	6.7	6.9	7.5	8	8.3
Finger III dia (in)	0.77	0.79	0.85	0.93	0.96

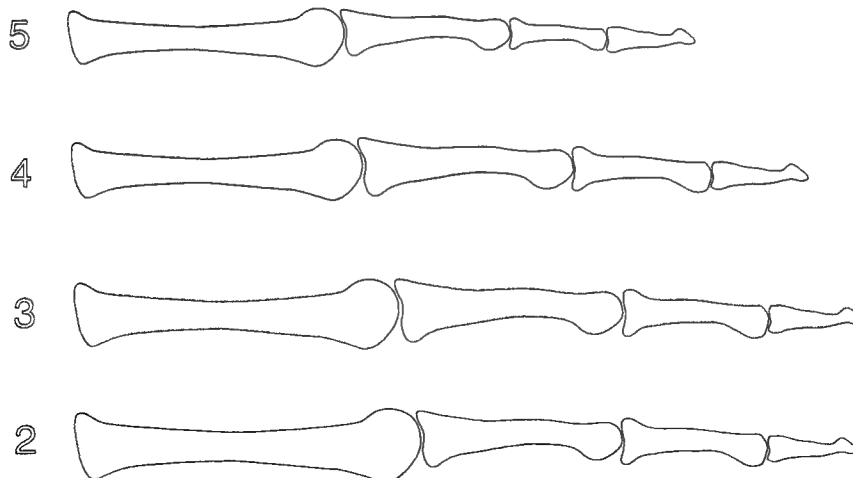


Figure 2.

In order to verify the fact that the model sizes derived from Poznanski are compatible with Air Force personnel, we can apply the linear model established by Buchholz to the percentile hand sizes from the Air Force study.

<i>PERCENTILE</i>	Hand Length (in) (Hertzberg)	Hand Length (mm) (converted from Hertzberg)	Digit II (index) mid phalange length (mm) HL*0.143 (Buchholz)	Segment Length (Poznanski)
1%	6.7	170	24.3	--
5%	6.9	175	25	--
50%	7.5	190	27.2	26.1
95%	8	203	29	--
99%	8.3	211	30.1	--

The segment length of the general male population, as measured by Poznanski, is approximately one millimeter shorter than that of the male Air Force Personnel when the model of Buchholz is applied to digit II. Results from other digit comparisons are similar. The approximation derived from Buchholz's model is relatively consistent (within 1 mm), and therefore both sets of data will be used in determining optimal hand sizes and variation in this study.

#### PHALANGE AXIS OF ROTATION

The axis of rotation of the phalangeal joints have been modeled as both fixed by some authors (Flatt et al. 1968, Youm 1978, Micks et al. 1978) and variable by others (Walker et al. 1975, Pagowski et al. 1977, Tamai et al. 1988). Where variability exist, they are small enough to ignore for many model applications (within 1.5 mm). In this application, it is not likely that glove stability and fit will hinder drift of an axis of rotation of that magnitude, and therefore a fixed axis model is adequate for these distal segments.

If the rigid mechanism is centered over the middle phalanges, then the variation over 90% of the population (+/- 2mm for digit II) will be distributed across two joints, and allow a fixed center of rotation to fall within a millimeter of its actual location. adjustability of this segment, therefore, would be on the order of one or two millimeters, and is not necessarily required. Variability of hand size is more a function of the proximal phalanges (+/- 4mm) as well as the metacarpals (+/- 7mm), and adjustability will be a key design feature at those locations. These two segments alone account for over 70% of hand size, and must be accommodated to achieve an accurate and effective fit. The remaining variation on hand size is accounted for by the distal



phalanges, which will not need to be accounted for, providing an open-tip exoskeleton is designed.

The joint center can be estimated by a linear model, by multiplying the segment length by a constant, giving the joint center as a distance from the base of the bone.

#### JOINT CENTER CONSTANTS:

Digit	Joint 1*	Joint 2*	Joint 3*
I	--	0.832	0.85
II	0.9**	0.909	0.89
III	0.9**	0.91	0.89
IV	0.9**	0.91	0.9
V	0.9**	0.9	0.87
II-V	0.9**	0.91	0.89

\* for digit I, joint 1 is CMC, joint 2 is MCP, and joint 3 is IP. For digits II-V, joint 1 is MCP, joint 2 is PIP, and joint 3 is DIP (Buchholz, 1992)

\*\* (Youm et al. 1978)

#### MIDDLE PHALANGE EXOSKELETON

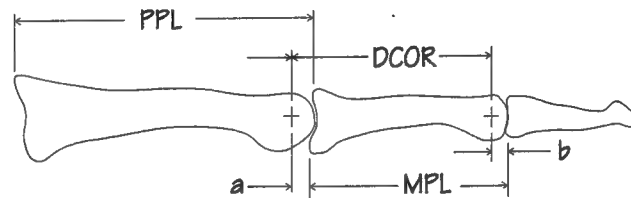


Figure 3.

A fixed length segment towards the distal end of the exoskeleton will accommodate both the PIP joint and the DIP joint. The length of this segment will be equal to the distance between the two centers of rotation. The centers of rotation can be found through a linear model (Buchholz, 1992) with the following results:

#### MALE:

Digit	MPL	PPL	PIPK	a	DIPK	b	DCOR
5	21.6	36.3	0.9	3.7	0.87	2.8	22.5
4	29.6	45.5	0.91	4.2	0.9	3.1	30.7
3	31.1	48.5	0.91	4.3	0.89	3.3	32.1
2	26.1	43.7	0.91	4	0.89	3	27.1

MPL = Middle Phalange Length

PPL = Proximal Phalange Length

PIPK = the PIP center of rotation constant ( $PIPK * PPL = PPL - a$ )

DIPK = the DIP center of rotation constant ( $DIPK * MPL = MPL - b$ )

DCOR = Distance between Centers of Rotation

#### FEMALE:

Digit	Mpl	Ppl	PIPK	a	DIPK	b	DCOR
5	18.7	32.5	0.9	3.3	0.87	2.4	19.6
4	26.4	40.8	0.91	3.8	0.9	2.8	27.4
3	27.9	44	0.91	3.9	0.89	3.0	28.8
2	23.2	40	0.91	3.6	0.89	2.6	24.2

Given the data on hand size and variability, it is conceivable to approach the design of the hand exoskeleton as adjustable at the proximal end (over the metacarpals and proximal phalange) and fixed-length at the distal end (over the middle and distal phalanges). The length of the fixed segment will correspond to DCOR.

#### RANGE OF MOTION

Although the ranges of motion of the joints in the hand are well documented, the question of functionality is usually left unaddressed. Information is available, however, which documents the actual range of the finger joints necessary to perform functional tasks (Hume, 1990).

ROM	Normal (deg)	Functional (deg)
Thumb MCP	56	22
Thumb IP	73	19
Finger MCP	100	62
Finger PIP	105	63
Finger DIP	85	39

The tasks requiring this functional range of motion were: Holding a telephone, holding a can, using a zipper, holding a toothbrush, turning a key, using a comb, printing with a pen, holding a fork, holding scissors, unscrewing a jar, and holding a hammer. These results imply that a full functional range of motion of the hand is possible without maximizing the range of motion of each segment.

Pinch forces have been extensively reported in the literature for the index finger and thumb pinch, reportedly the strongest of all the fingers. In a review of several studies, the range of male hand pinch is between 30 and 100 N, depending on the pinch geometry. The joint forces measured in the human hand are 4.1 to 8.8 times the pinch load, as a result of the configuration of the tendons and reaction surfaces (Weightman, 1982). It will not be necessary for the maximum values of force applied to the hand by the exoskeleton to exceed these values.

#### ACTUATOR SELECTION AND CONTROL:

Currently, there are two commercially available dexterous hand masters, neither of which provide a mechanism for force feedback. One system, the VPL DataGlove, is a compliant structure which uses optical sensors and fiber-optic cables to transduce finger angles, while the other system, the Exos, Inc. Dexterous Hand Master (DHM), relies on rigid, mechanical linkages to transduce finger joint position angles (Burdea 1, 1991). Exos does provide a force feedback hand master, but not one that includes position sensing of the finger digits. The DHM has a resolution and accuracy which is reportedly superior to that of the DataGlove (0.1 deg vs 0.5 deg), presumably as a result of the decreased compliance.

In an apparently objective review of the DataGlove for the purpose of semi-automated goniometric measurements for physical therapy applications, the accuracy and repeatability of the device was evaluated (Wise, 1990). In their study, the authors reported significant differences in repeatability between subjects, and attributed the differences to the fit of the glove on different subjects. The repeatability of measurements supplied by the manufacturer is +/- 5 degrees. Removing or keeping the glove on between measurements had little effect on the repeatability of the measurements, indicating the fact that any differences in fit of the glove are probably due to slipping and reorientation of the hand during the test, and not initial application of the glove itself. This is further substantiated by the fact that the gripping force had an effect on the transduced position of the joints as well, with angles varying by as much as 11 degrees with different force application at the same joint position. Additionally, it was found that wrist flexion and extension affected the measurements of the glove. The compliance offered by a flexible structure such as the DataGlove may provide significant advantages with regards to comfort and flexibility, but brings significant disadvantages as well, including the repeatability and accuracy of the transduced joint angles.

COMPLIANT	RIGID
Flexibility, various sizes	must be adjusted to fit
inaccurate force transmission	positive force transmission
lack of sensitivity	very sensitive
lack of resolution	high resolution
must be calibrated to user fit	possibility of no calibration
lightweight	lightweight given certain materials

The drawback of a rigid structure is the lack of adaptability to the various sizes of hands which will encounter it. A review of anthropometric hand sizes has shown that hand size variability is mostly accounted for at the proximal segments, where adjustability will be mandatory. It is conceivable that a *fixed length distal segment* interface may be able to accommodate 95% of the population without compromising the accuracy of the position transduction.

Another area of interest related to Force feedback is that of tactile feedback. It is the opinion of the author that the ideal force actuator would also be capable of providing the frequency response for both tactile and force feedback. The human is capable of discriminating vibrations up to about 300 Hz. And of sensing vibrations up to approximately 10KHz. There are no gear motors appropriately scaled to the dexterous feedback which can provide 300 Hz vibrations. The inchworm motor developed in this project does have that capability. Thus it could become important to provide means of measuring joint angle from 0 to 300 Hz at very small amplitudes.

### Finger Forces

There continues to be some discussion among researchers as to what Force values should be used as design criteria for dexterous force feedback. The measurement of maximum joint forces has been conducted and is reported in the range of 40 N (9 lb) for the index and middle fingers. It is generally agreed that for most applications a force less than the maximum would be desirable to avoid possible damage to the joints and to reduce motor requirements. Recent review of the PHANToM by Hasser elicited favorable results with forces substantially (20%) lower than the maximums. Hasser has also begun an interesting comparison of actuator technologies by studying not only the force but the power (joint torque x joint velocity) required by the joints and the candidate actuators. His estimates show a requirement ranging from 1 watt at the lower end up to 21 watts for the maximum.

## Task 2. Resistive Actuator Development

To accomplish the goal of force feedback, both active and resistive actuation are desirable. An example of an active actuator is one that actively drives a joint, and a resistive actuator is something that simply resists joint movement. The main objective of this project is to develop a device that utilizes Terfenol-D and that could be used as both an active and resistive force actuator. During the preceding Phase I project we had evaluated the concepts of resistive force feedback (brake only) as an independent concept from active (motor driven) feedback. In Phase II we began by joining these two concepts. A three element inchworm motor consists of two brakes and a pusher element. During this project to develop actuators applicable to telerobotic manipulation we broke the study down into the study of resistive elements (brakes) and active elements (moving shaft). In this case the brake is to be activated by using the induced strain in Terfenol-D as the brake piston.

Terfenol-D is a magnetostrictive material. As the magnetic field increases, the induced strain in Terfenol-D increases up to a certain field strength. At that point, the Terfenol-D is saturated and any increase in magnetic field will not improve the strain. Apparent in Figure 4 is the effect of a prestress or preload on Terfenol-D. A higher strain is achieved when a preload is placed on the Terfenol-D rod. "These compressive loads serve to orient the magnetization perpendicular to the rod axis in zero field in order to achieve a full 90° rotation of the magnetization with fields applied along the rod axis" [Clark].

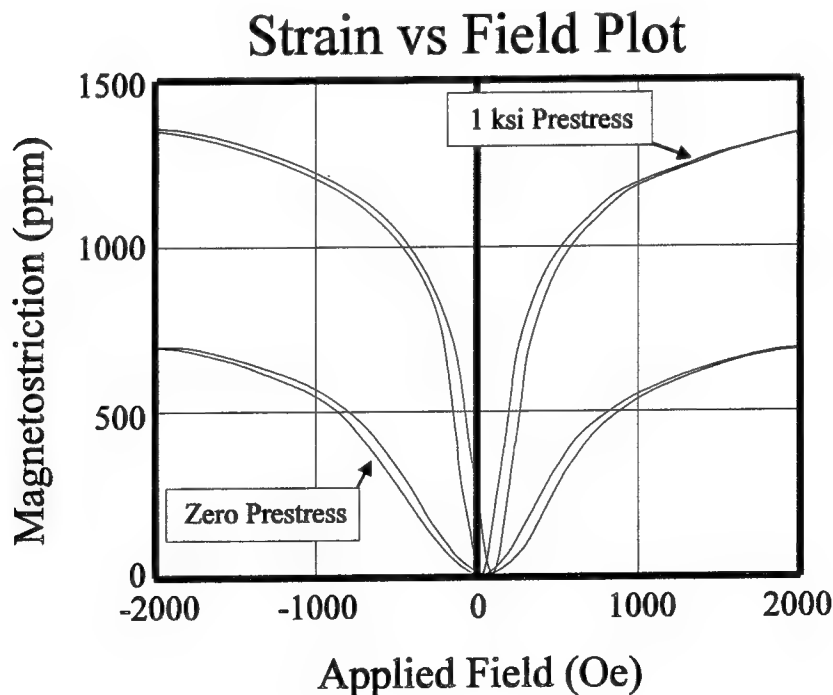


Figure 4.

Aside from its high strain, Terfenol-D lends itself quite well to use in linear actuators because of its mechanical properties. The following table lists some of the properties of Terfenol-D as established by ETREMA Products, Inc.

Properties of ETREMA Terfenol-D [Butler].

Property	Value
Bulk Modulus	$9 \times 10^{10} \text{ N/m}^2$
Tensile Strength	28 MPa
Compressive Strength	700 MPa
Magnetostriction	1500 - 2000 ppm
Energy Density	$14 \times 10^3 - 25 \times 10^3 \text{ J/m}^3$
Curie Temperature	380°C
Magnetization	1.0 T

#### Brake Element Design Constraints:

There are specific design constraints inherent with both Terfenol-D and dexterous hand exoskeletons. Some of these constraints are as follows:

1. Size constraints of a hand exoskeleton.
2. Limited displacement of Terfenol-D rods.
3. Required preload for optimal Terfenol-D performance.
4. Provisions for magnetic return path.
5. Desired frequency response to match finger/hand velocities.
6. A flexure design that limited localized stress concentrations in Terfenol-D rod.
7. Infinite fatigue life.

1. Size constraints of a hand exoskeleton (i.e. a motor mounted on a joint).

The ideal exoskeleton would be a device where the motors that are controlling joint motion are located at the joints that they actuate. When motors are located away from the joint that they actuate, energy and precision losses due to friction and slack are introduced into the system. Frequency responses would also be limited with the addition of mechanical linkages. The ideal motor, then, would be small enough to be mounted effectively on a finger joint, yet have sufficient power to provide the necessary actuation.

2. Limited displacement of Terfenol-D rods.

Terfenol-D is magnetostrictive and undergoes a strain when exposed to a magnetic field. The relationship is:

$$\text{Strain} = (d \text{ constant})[(\text{magnetic field})(1000)/(4)] \quad [\text{Butler}]$$

As a example, a Terfenol-D rod that is 0.5 inches (1.27 cm) long and 0.1 inches (0.254 cm) in diameter, in a 1000 Oe magnetic field would undergo a strain of  $1.60 \times 10^{-3}$  ppm along it's axis.

$$\text{Strain (S)} = (2.0106 \times 10^{-8})[(1000)(1000)/(4)] = 1.60 \times 10^{-3} \text{ ppm}$$

This strain equates to a change in rod length of:

$$\Delta \text{Length} = (\text{Initial Length of Terfenol-D rod})(S)$$

$$\Delta \text{Length} = (0.500 \text{ inches})(1.60 \times 10^{-3}) = 0.0008 \text{ inches (0.002 cm)}$$

### 3. Required preload for optimal Terfenol-D performance.

It has been shown that Terfenol-D's performance improves when an initial preloading or prestress is applied to the rod. When a preload (prestress) is applied, the Terfenol-D rod displays a much larger strain for a given magnetic field. In Figure 4, the strain at no preload and at a 1000 psi (6.895 MPa) preload is shown. It can be seen that with the added prestress, the strain for a given magnetic field is significantly larger than without the prestress.

"Magnetostriction is a result of the rotation of small magnetic domains which causes internal strains in the material. The strains result in a positive expansion of Terfenol-D in the direction of a magnetic field. As the field is increased, more domains rotate and become aligned until finally saturation is achieved, where nearly all domains are aligned in the direction of the field" [Butler]. A compressive load, or prestress, serves to "... orient the magnetization perpendicular to the rod axis in zero field in order to achieve a full 90° rotation of the magnetization with fields applied along the rod axis" [Clark]. In simpler terms, the magnetic domains are initially not all oriented perpendicular to the rod, but at some angle  $\phi$ . The compressive load compresses the material and orients the magnetic domains perpendicular to the rod axis. This allows the magnetic domains to rotate over the full 90°, instead of  $(90^\circ - \phi)$ , which produces a greater change in length (strain).

### 4. Magnetic Circuit.

The magnetic circuit was studied to enhance efficiency. Basically the most efficient magnetic solenoid circuit is achieved by trapping the magnetic flux lines in a permeable circuit and eliminating permeability through free space. For this purpose a small end cap is placed on the ends of the Terfenol-D and coil. Experiments to confirm effectiveness of the design are illustrated in the photographs.

5. Desired frequency response due to speeds of human hand.

To obtain the linear motor velocities that are needed to provide both active and resistive actuation of the human hand, the actuator must operate within the range of 5 Hz to 10 KHz. Shimoga suggested that the slave fingertip forces be presented to the human hand by the master device at 20 - 30 Hz. He also suggested that "... chattering could only be felt if signals are presented to the hand within the range of 300 - 400 Hz, while the corresponding bandwidth for fine vibrations is 5,000 - 10,000 Hz. The ideal hand master must be able to use all these bandwidths in accordance with the situation."

6. Preload string (flexure) designed such that undue local stress are not introduced to the Terfenol-D rod.

Another requirement in this design is that of maintaining the flexure surface parallel to the Terfenol-D rod. If the middle section of the flexure is distorted by the movement of the Terfenol-D rod, local high stress regions are introduced that could lead to metal fatigue and failure. This concept is illustrated in Figure 6. Here a Finite Element Model (FEA) of a flexure is being displaced by a rod and the mating surfaces are not parallel. This condition produces local high stress concentrations that could fracture the brittle Terfenol-D material.

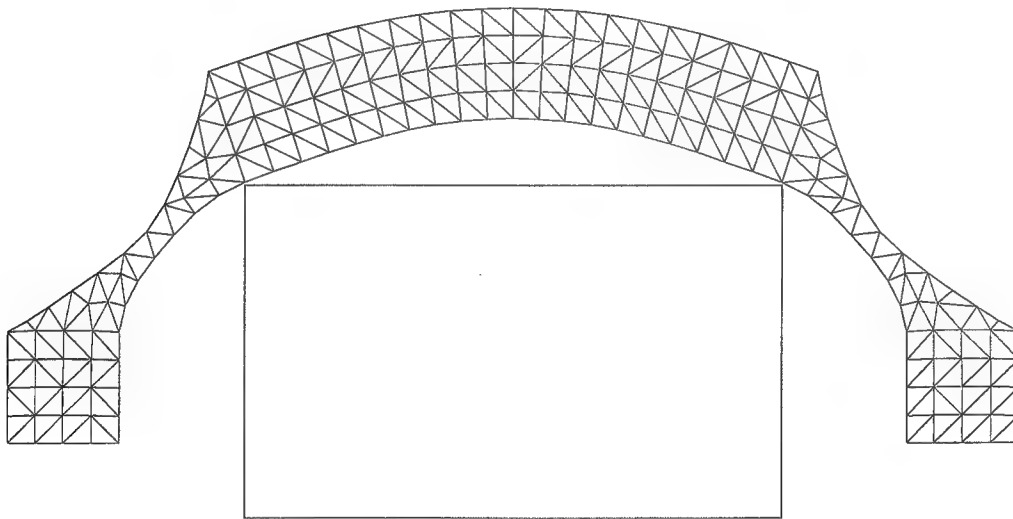


Figure 6: Finite Element Demonstration of Non-Parallel Surfaces

7. Designed for Infinite Fatigue Life.

One other important design consideration is that of designing for infinite fatigue life. The material selection and mechanical design must be such that allows for an infinite number of cycles without a fatigue failure. "Fatigue failures result from repeated plastic deformation. An



example of this is the breaking of a wire by bending it back and forth. Fatigue failures typically occur after thousands or millions of cycles of minute yielding. It can occur at stress levels far below the conventionally determined yield point or elastic limit. The endurance limit of a material is defined as the highest level of alternating stress that can be withstood indefinitely without failure"[Juvinall].  $S_n$  is the symbol used to designate endurance limit. A S-N curve, (stress - number life cycles), for steel can easily be approximated with a knowledge of the ultimate tensile strength. From this curve, the endurance limit can be obtained. The relationship is

$$S_n = 0.5S_u$$

where

$S_n$  = endurance limit

$S_u$  = ultimate tensile strength

Figure 7 illustrates an example of a generic endurance limit curve for steels. Any stress level below the endurance limit of  $0.5S_u$  can theoretically cycle indefinitely without a fatigue related failure.

The stress component (value) to be considered in this analysis is the Von Mises stress. Von Mises stresses are related to the Maximum Distortion Energy Theory. This theory states that "... any elastically stressed material undergoes a slight change in shape and/or volume. The energy required to produce this change is stored in the material as elastic energy. It was recognized early on that engineering materials could withstand enormous hydrostatic pressures (i.e.  $\sigma_1 = \sigma_2 = \sigma_3 =$  large compression) without damage. It was therefore postulated that a given material has a finite capacity to absorb energy of distortion (i.e. energy tending to change shape but not size), and that attempts to subject the material to greater amounts of distortion energy result in yielding [Juvinall].

When using this failure theory, it is convenient to work with an equivalent stress or a Von Mises stress. This stress is defined as the value of uniaxial tensile stress that would produce the same level of distortion energy as the actual stresses involved. The equation for this Von Mises stress is as follows:

$$\sigma_{vm} = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \sigma_1\sigma_2 - \sigma_2\sigma_3 - \sigma_3\sigma_1}$$

where  $\sigma_1 > \sigma_2 > \sigma_3$

### Fatigue Limits

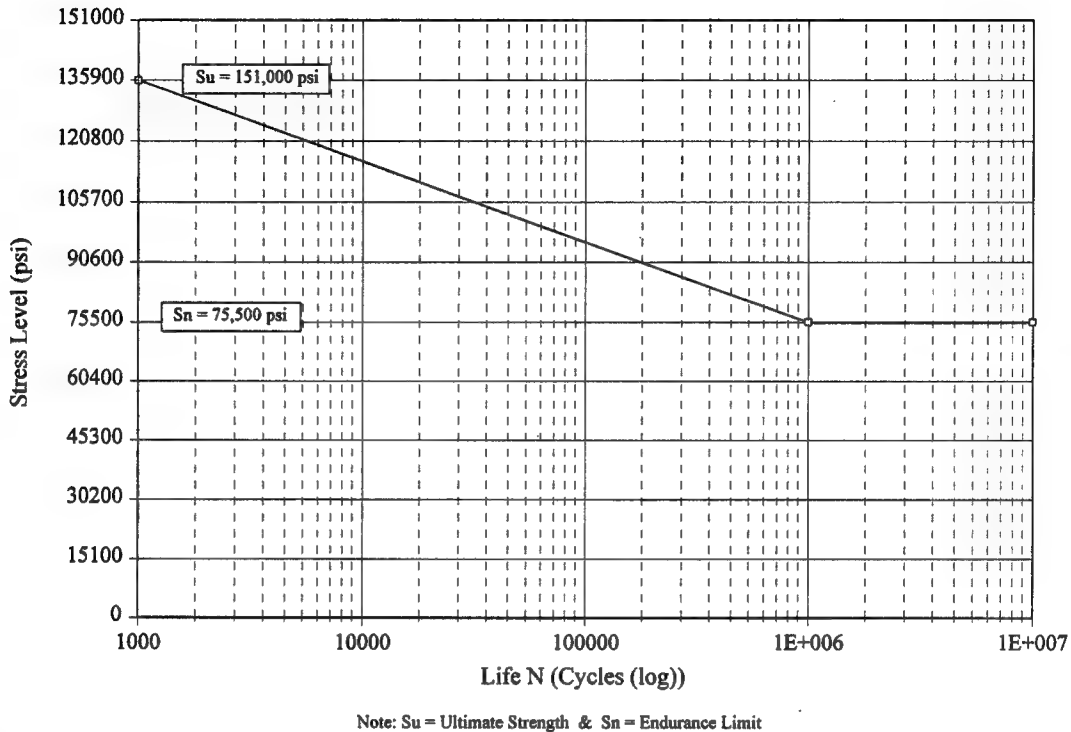


Figure 7: Typical Endurance Limit Curve For Steel

### Magnetic Coil Design Criteria

To maximize the performance of the Terfenol-D rods, the magnetic coil design needs to be optimized for size, current and voltage, and several potential failure related challenges need to be resolved. The basic objectives of the coil design are:

1. To achieve a 1000 Oe field through the Terfenol-D rod.
  2. Have the coil geometry compatible with the actuator housing geometry.
  3. Have the current and voltage requirements within an acceptable range (based primarily on available equipment to drive the coils).
  4. Provide protection to the coil to prevent failures.
- ♦ thermal
  - ♦ mechanical
  - ♦ electrical

As can be seen in the Strain vs. Magnetic Field Plot in Figure 1.1, 90+ percent of the strain is achieved when the magnetic field is 1000 Oe. Above 1000 Oe, little improvement in

strain is achieved. Additionally, stronger magnetic fields require more current through the coil which produces more heat.

The coil geometry must be such that it optimizes the available space in the actuator housing, yet can still be inserted and removed without damaging the windings.

The current and voltage required to drive the coil are dependent on the resistance of the coil, which is largely determined by the wire gauge used. The goal is to have a current less than 5 amps, and a voltage less than 10 volts.

Large amounts of heat will be generated because of inefficiencies in the coil and the Terfenol-D material. As the coil and Terfenol-D heat up, several things could happen. First and most likely is that the coil will burn up and no longer provide the needed magnetic field. Secondly, the magnetostrictive effect of the Terfenol-D rod falls off linearly as the temperature approaches the Curie point<sup>4</sup> which is approximately 715°F or 380°C [Goodfriend]. As the temperature of the rod approaches the Curie temperature, the efficiency of the rod drops off until it is no longer useful.

Mechanical failure could result if there is relative motion between the Terfenol-D rod and the magnetic coil. In order to miniaturize the actuator, the device must be extremely small with close tolerances. As the rod moves up and down at 5 KHz to 10 KHz, friction can wear the insulation off the coil and cause an electrical short. Early devices failed in this mode. The coil and Terfenol-D were insulated using a Teflon barrier both insulate and mechanically isolate the two components to ensure that the wearing is minimal and that no electrical shorts occur.

The design goal for this task was to develop a modular brake actuator that could also be used as the prime mover in a small, linear motor. The final motor concept in mind was an *inchworm* motor. One such configuration consists of two brakes and a mover. One brake locks the motor position onto a drive shaft and the mover then advances (stretches) the motor forward. While the motor is stretched forward, the other brake clamps down on the shaft and the first brake releases. The process is then again repeated many times over. In this manner the motor will *inch* forward in a method somewhat similar to an inchworm in nature.

As the movers in a small motor, this actuator must convert the electrical energy of the coil into a small motion, or change in length of a rod in this case. The motions that will be present are on the order of 0.001 - 0.002 cm (0.0004 - 0.0008 inches). These tiny motions require a device with extremely tight tolerances and an exceptionally efficient mechanical transfer of motion between components.

It was determined that the brake actuator would be based on a flexure configuration. As the Terfenol-D expands, the supporting mechanical structure (housing) must expand with it and then contract back with it as it contracts. This would be necessary to provide a good frequency response and preload. Other actuators that have been developed using Terfenol-D, used springs and plates to provide the preload and stiffness needed to reset the mechanical structure. These devices are relatively large and bulky and have a frequency response that is not suitable for operation on a finger or hand. They also would be prone to inefficiencies due to slack in the system and low energy transfers from mating parts.

A properly designed flexure would be constructed out of one continuous piece of metal and would not have slack, looseness, or low mechanical energy transfer. It would have the spring built into the housing which would allow better control of stiffness and ultimately frequency response. It would also provide the necessary preload to the Terfenol-D rod.

The design of the brake module, dubbed "motive cell", was broken into three (3) basic components: The flexure, the housing (housing, end cap, and magnetic return path) and the coil.

### Flexure

The flexure design was initiated with a simple, 2-D (2 dimensional) baseline design. This design can be seen in Figure 8. What followed next was an iterative process of modification and analysis.

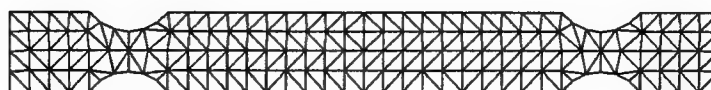


Figure 8: 2-Dimensional Baseline Flexure Design

COSMOS/M Explorer, a Finite Element Analysis (FEA) software package that was used for theoretical determination of stresses, strains, and resonant vibrations modes. The performance criteria used in this iterative design sequence were:

- ♦ To maintain the stress levels within a specified safety margin to ensure an infinite fatigue life.
- ♦ To create a motion that was stable and maintained a surface parallel to the Terfenol-D rod so as not to create undue stress concentrations. What was desired was essentially a button of metal that moved up and down with the expanding and contracting Terfenol-D rod.
- ♦ The flexure is designed to have a vibrational response up to 10 KHz to achieve the desired motor velocity. The following flow chart illustrates the sequence followed in this iterative design process.

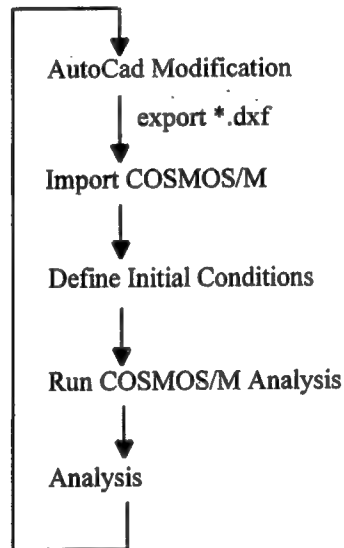


Figure 9: Analysis Flowchart

The following documents the process used in the development of the flexure.

#### 1. AutoCad Modifications

The initial flexure design and each subsequent modification was made using AutoCad. The 2-D designs were then exported as \*.dxf files.

## 2. Import into COSMOS/M

The \*.dxf file was imported into COSMOS/M.

## 3. Define Initial Conditions

The initial conditions had to be defined with each revision. These initial conditions are:  
Material Properties: Alloy Steel 4340 with elastic modulus ( $E$ ) = 30,000,000 psi; ultimate strength ( $S_u$ ) = 151,000 psi; yield strength ( $S_y$ ) = 132,000 psi; and Poisson's ratio ( $\nu$ ) = 0.28.  
Loading Conditions: Each flexure was loaded with a 1000 psi load and a 2000 psi load.  
Boundary Constraints: The ends (outside edges) of the flexure, where the housing would attach, were constrained to not move. The flexure itself was allowed to move in all directions.  
Element Type: 4 node tetrahedron

## 4. Perform COSMOS/M Analysis

Both the stress/strain and the frequency analysis were performed. The conditions that were looked for are:

- ♦ Stress within acceptable limits. (for infinite fatigue life)
- ♦ Strains within acceptable limits.
- ♦ Frequency of first and second harmonic.
- ♦ Was a surface maintained parallel to the Terfenol-D rod?

After many iterations, an acceptable 2-D design was obtained. This design can be seen in Figure 10. (Show both undeformed and deformed modes) This design was then modeled in three (3) dimensions to confirm the validity of the 2-D design, and to determine how to deal with hoop stresses in the flexure.

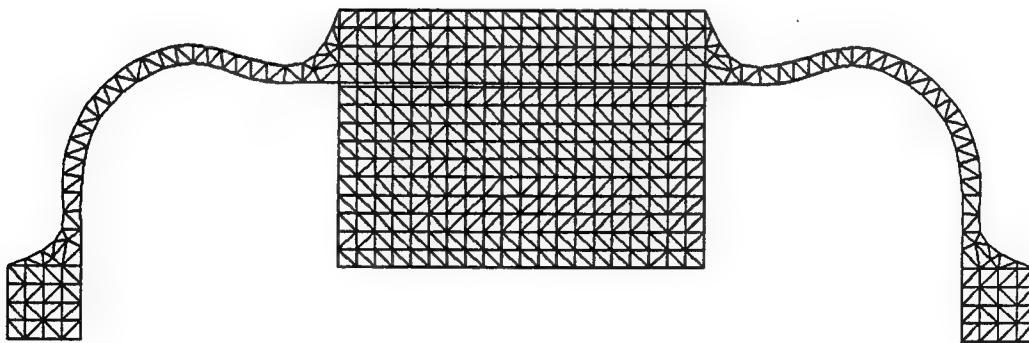


Figure 10: Final 2-D Flexure Model

Hoop stresses were a particular problem with this design. This was because of the motion of the flexure. As the flexure moved up, extreme stresses developed along the "S" portion of the flexure. To resolve this problem, slots were designed into the flexure that radiated out from the center disk every 35° and were 10° wide. This alleviated the severity of the hoop stress problem. A sketch of the final 3-D design with the slots can be seen in Figure 11.

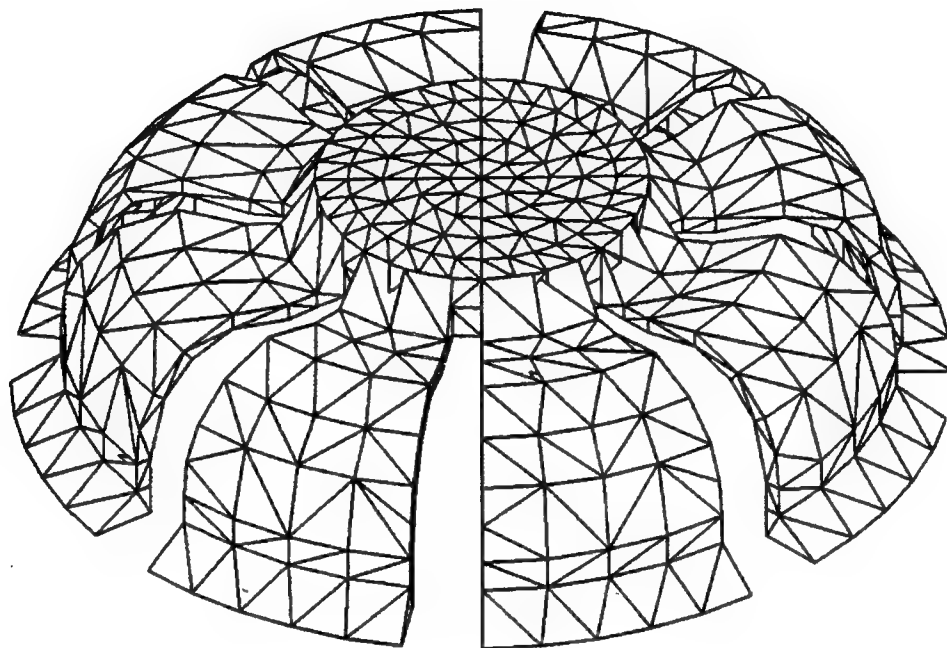


Figure 11: Final 3-D Flexure Model

The results from the final 3-D flexure FE analysis are as follows:

	Loading 1	Loading 2
Maximum stress (Von Mises) =	17,350 psi	34,701 psi
Maximum strain =	0.0002 inch	0.0004 inch

### Analysis of Final Three Dimensional Design

As stated earlier, the Von Mises stress is an equivalent tensile stress for the material. A stress - strain curve for alloy steel 4340 is illustrated in Figure 12. It should be noted that the Von Mises stress levels for both loading conditions are well below the yield stress of the material. This indicates a safety factor of at least 2 for these conditions.

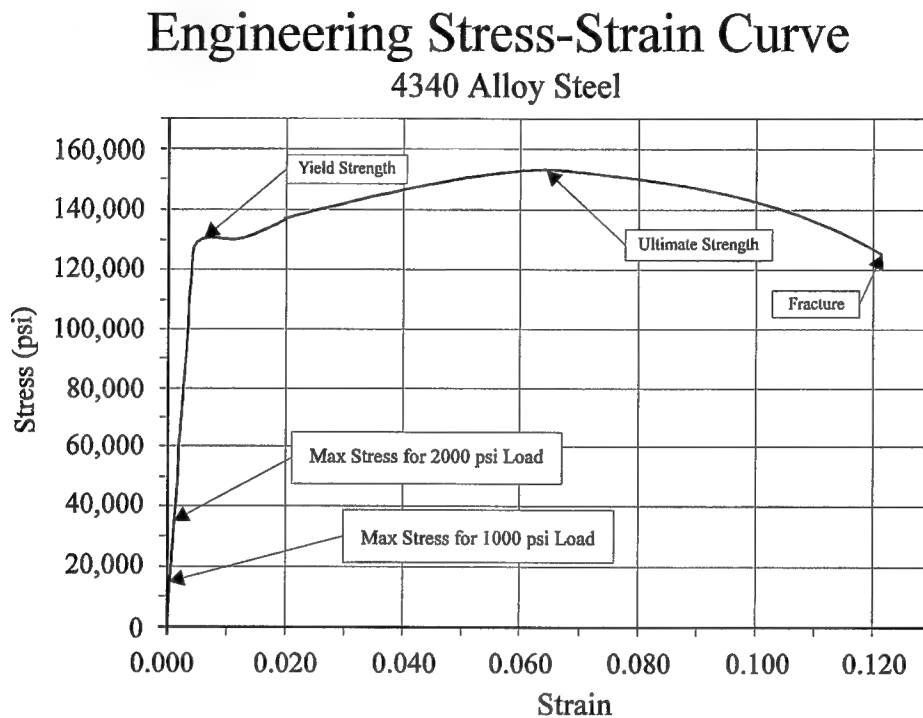


Figure 12: Stress-Strain Diagram for Alloy Steel 4340.

Figures 13 and 14 are the COSMOS/M results on screen. Figure 13 is a front view of the flexure displaying the Von Mises stress levels. Figure 14 is the back side displaying the same. It can be seen that there are specific regions of high stress. This is the region where the hoop stresses are still present, but are within acceptable ranges.



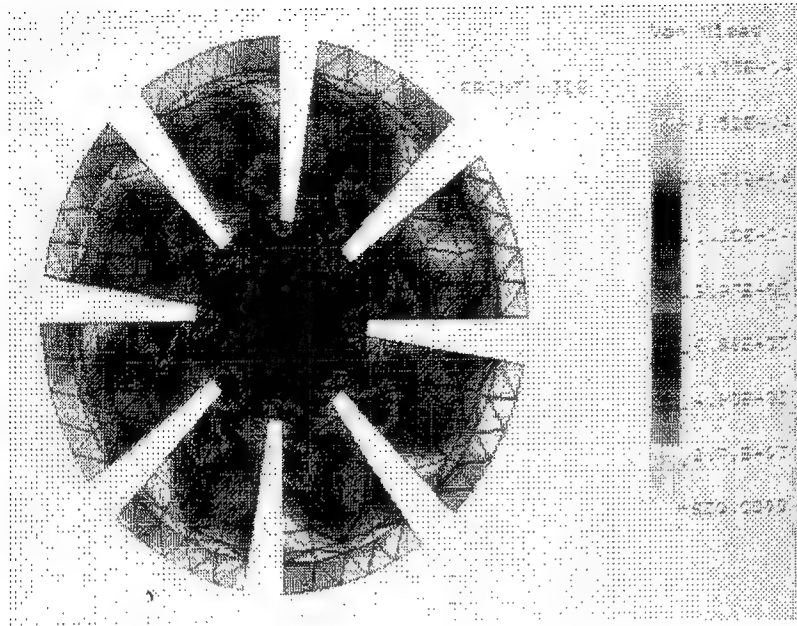


Figure 13: Front View of Flexure Displaying Von Mises Stress Levels.

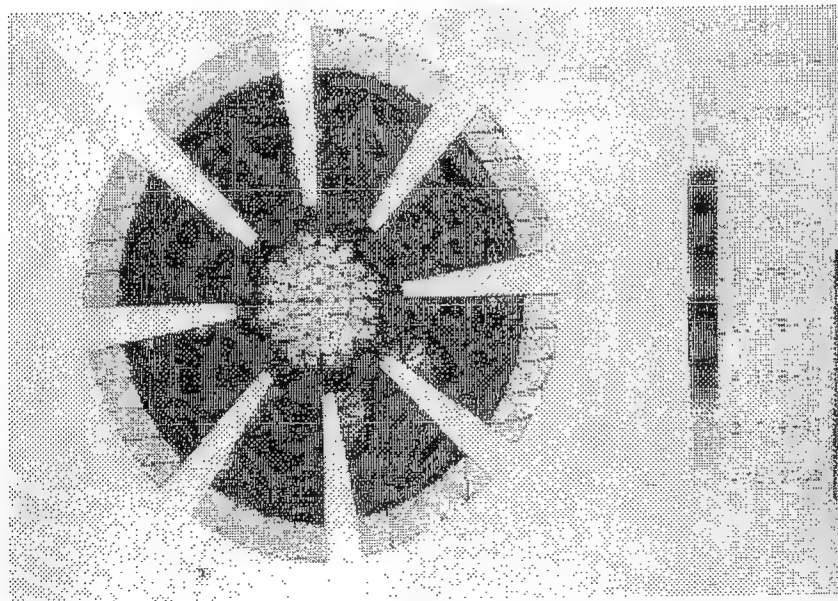


Figure 14: Back View of Flexure Displaying Von Mises Stress Levels.

## Fatigue - Endurance Limit

The endurance limit of a material is defined as the highest level of alternating stress that can be withstood indefinitely without failure. For this material, the endurance limit ( $S_n$ ) = 75,500 psi. This means that any stress condition below this level can theoretically cycle indefinitely without a fatigue related failure. This can be seen clearly in Figure 15, an endurance limit plot for alloy steel 4340.

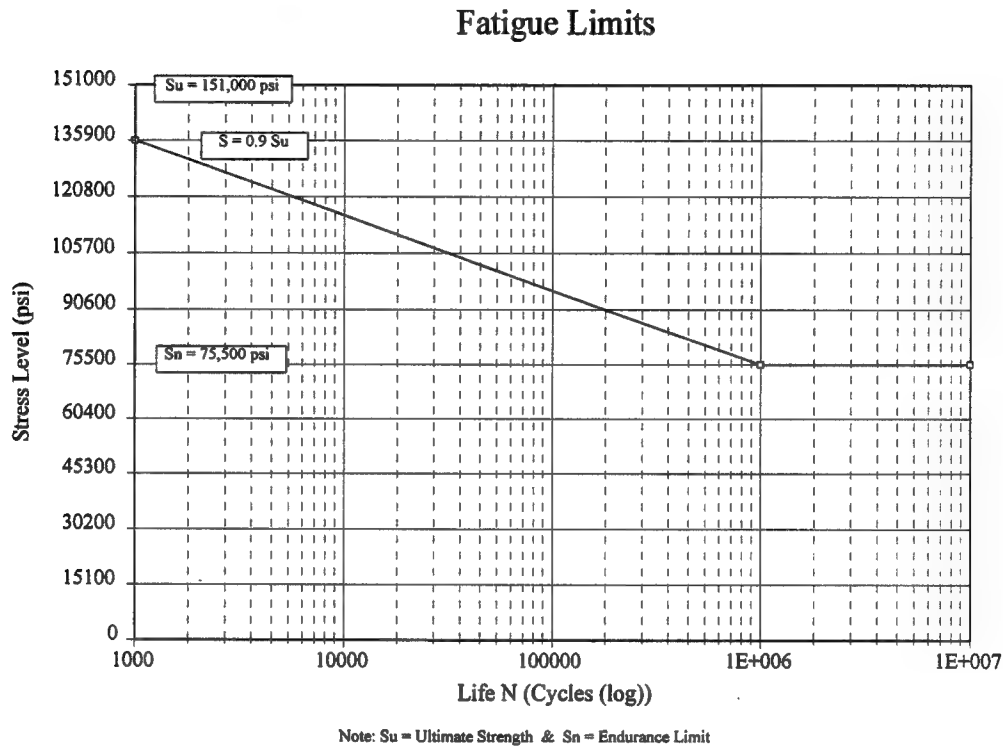


Figure 15: Endurance Limit Plot for Alloy Steel 4340.

The flexure continued to be improved over the course of the project. The final flexure used in the motor had significantly reduced hoop stress due to the use of more radial slices.

## Motive Cell Housing and Accessories

The housing for the motive cell plays an important role in the functionality of the device. It has to:

- Provide an external housing to the Terfenol-D rod and the coil.
- Provide a magnetic return path which encourages the flux lines back through the Terfenol-D.
- Provide a preload to the Terfenol-D rod (in conjunction with the flexure).
- Provide a means of securing the device to the structure upon which it will act.

A wall thickness of 0.030 inches for the external housing was chosen and tested using COSMOS/M. It was found to be adequate in that it did not deform significantly under the loading conditions. The wall thickness also provided adequate space for threading the diameter.

Several sizes were studied as we developed the final concepts. It was decided that two different size actuators would be developed for the final inchworm device. The only difference would be the length of the Terfenol-D rod. The two sizes chosen are:

1. A Terfenol-D rod that is 0.25 inches long and 0.10 inches in diameter.
2. A Terfenol-D rod that is 0.50 inches long and 0.10 inches in diameter.

The expected displacement of a Terfenol-D rod is proportional to the length of the rod. Therefore, a rod that is twice as long, with the same diameter, will produce twice the displacement.

#### Magnetic Return Path:

In order to insure that the electromagnetic coupling is not too lossy features had to be built into the device which forced these flux lines back through a more efficient circuit. On the end of the housing opposite the flexure, a threaded end cap was placed. This end cap screwed into the housing and would provide the magnetic return path on this end of the rod. It would also provide a means of adjusting the compressive preload on the Terfenol-D rod.

At the flexure end of the Terfenol-D rod, the flexure itself would act somewhat as a magnetic return path, but the cross-sectional surface area of the flexure was so small that it was not sufficient. Another piece of metal was added between the flexure and the Terfenol-D rod to provide the definitive magnetic return path. It would also act as a buffer/bearing between the brittle Terfenol-D rod and the flexing flexure.

#### Coil Design

The coil plays an important role in the function of this actuator because it provides the magnetic energy needed to induce the strain on the Terfenol-D rod. Even though the main criteria for the coil is that it needs to generate a 1000 Oe field through the Terfenol-D rod, there were several other challenges that presented more of a problem. Some of them are:

- A coil winding apparatus must be developed for custom windings.
- The coil geometry must be compatible with the motive cell;
- The current and voltage requirements must be at reasonable levels;
- The coil must be protected against thermal, mechanical and electrical failures.

Programs were written in software to help automate iterative calculation for coil configurations. The software is included in an appendix.

### Coil Winding:

In early prototype actuators, the coils were wound around a small nylon spool that was machined on the lathe. A representation of this method can be seen in Figure 16. These prototypes, however, were considerably larger and were not optimized for size. The challenge here was to develop a method of winding extremely small coils that could be slipped on and off of a Terfenol-D rod, yet take up the least amount of space as possible. This meant that the coils had to maintain their physical integrity without a supporting structure like a nylon spool.

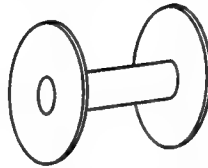


Figure 16: Nylon Spool Upon Which Coils Were Wound

### Bondable Wire:

A solution to part of this problem was found in a bondable wire manufactured by MWS Wire (Westlake Village, CA). This bondable wire is copper magnet wire that is film coated with an insulation and has an additional coating of a thermoplastic adhesive. The thermoplastic adhesive is activated by either using a specific solvent, or by heating the wire beyond a specific temperature. This heat bonding can be accomplished by passing a current through the winding to achieve the desired bonding temperature. The specific insulation used was a polyurethane-nylon that has a temperature rating of 130°C. The bondable overcoat used was a polyvinyl butyral that has a heat activation temperature of 120°C. The maximum continuous operating temperature of the wire is 105°C.

By using this bondable wire, small coils were wound that did not require a special spool and could be slipped on and off the Terfenol-D rods.

### Coil Winder:

To wind the coils, a small mandrel was machined that held the dimensions of the coil until the wire could be heat bonded. This mandrel was placed in a chuck which was driven by a variable speed DC motor. A counter was attached to the chuck to digitally count revolutions or coil windings. Bonding was accomplished by passing approximately 1 amp of current through the coil.

### Visualization:

With the smaller coils, often it was difficult to visualize the winding process because of the size. A video camera with a macro zoom lens was placed above the coil being wound and the image displayed on a 25 inch screen television. This allowed the individual winding the coil to see close up what was happening.

### Coil Geometry Compatible with Actuator Housing:

The coil should have to be as large as it possibly can, yet still slip in and out of the actuator housing. The inside diameter of the housing is 0.25 inches and the outside diameter of the Terfenol-D rod is 0.1 inches. Therefore, the coil outside diameter should be around 0.240 inches, and the coil inside diameter should be around 0.10 inches.

### Current and Voltage Levels:

#### Wire Gauge Optimization

The next major challenge was choosing the optimum wire gauge for the coil. The desired magnetic field was 1000 Oe, and voltage, current, and resistance values had to be maintained within a manageable range.

An iterative software process was followed to determine which wire gauge size was optimum to meet the design objectives. Using the Terfenol-D rod that was 1.27 cm (1/2 inch) long and 0.254 cm (1/10 inch) in diameter as an example, a sample calculation follows. The maximum outer diameter of the coil was determined by the inside diameter of the motive cell, which was 0.635 cm (0.25 inch). This data limited the physical size of the coil. The desired magnetic field was 1000 Oe, which constrained the current and voltage inputs. Three (3) different wire gauge sizes were evaluated.

To determine the voltage and current inputs required to achieve a 1000 Oe field and calculate the expected response from the Terfenol-D rod.

#### Constraints:

Wire gauge = 30

Wire diameter = 0.011 inch

Coil length = 0.500 inch

Coil OD = 0.240 inch

Coil ID = 0.100 inch

Wire resistance = 0.1032 ohms/ft

Desired magnetic field = 1000 Oe

**Number of Wire Turns:** The first calculation made was to determine how many turns could fit within the geometrically constrained space of the actuator.

#### Terms Definition:

OD = outside diameter

ID = inside diameter

$n_{len}$  = number of wire diameters that would fit in coil length

$n_{dia}$  = number of wire diameters that would fit in coil diameter

$n_{\text{turns}}$  = number of wire turns in coil

$n$  = turns density (turns/length)

$\text{Res}_{\text{coil}}$  = resistance of coil

$S$  = strain

mag field = magnetic field

$\delta$  = change in rod length

$L_{\text{rod}}$  = length of rod

ppm = parts per million = a change in length of 50  $\mu$  inch / 1 inch of material length<sup>5</sup>

The number of wire diameters that would fit along length of rod:

$$n_{\text{len}} = (\text{length rod}) / (\text{OD}_{\text{wire}})$$

$$n_{\text{len}} = (0.5 \text{ inch}) / (0.011 \text{ inch}) = 45.45 = 45$$

The number of wire diameters that would fit between OD of the rod and OD of coil:

The number of wire turns in the coil:

$$n_{\text{dia}} = ((\text{OD}_{\text{coil}} - (\text{OD}_{\text{rod}} + 0.01 \text{ inch})) / 2) / \text{dia}_{\text{wire}}$$

$$n_{\text{dia}} = ((0.240 \text{ inch} - (0.1 \text{ inch} + 0.01 \text{ inch})) / 2) / 0.011 \text{ inch} = 5.91 = 6$$

$$n_{\text{turns}} = n_{\text{len}} * n_{\text{dia}}$$

$$n_{\text{turns}} = (45)(6) = 270 \text{ turns}$$

Length of Wire:

The length per layer of wire in the coil:

$$\text{Length}(\text{layer}) = ((\text{OD}_{\text{rod}} + 0.01 \text{ inch}) + (\text{Layer} * 2 * \text{OD}_{\text{wire}})) (\pi * n_{\text{len}})$$

$$\text{Length}(1) = ((0.1 \text{ inch} + 0.01 \text{ inch}) + (1 * 2 * 0.011 \text{ inch})) \pi = 18.66 \text{ inches}$$

$$\text{Length}(2) = 21.77 \text{ inches}$$

$$\text{Length}(3) = 24.88 \text{ inches}$$

$$\text{Length}(4) = 27.99 \text{ inches}$$

$$\text{Length}(5) = 31.10 \text{ inches}$$

$$\text{Length}(6) = 34.21 \text{ inches}$$

Total wire length = 158.61 inches

Coil Resistance:

$$\text{Res}_{\text{coil}} = (\text{wire length})(\text{resistance per ft})$$

$$\text{Res}_{\text{coil}} = \frac{(158.61 \text{ in (ft)}) (0.1032 \text{ ohms})}{12 \text{ in} * \text{ft}} = 1.364 \text{ ohms}$$

#### Current Through Coil / Voltage Across Coil:

$$n = \text{turns} / \text{length}_{\text{coil}}$$

$$n = 270 / 0.5 \text{ inch} = 540 \text{ turns/inch} = 21,259.84 \text{ turns/meter}$$

$$\text{Current} = I = (\text{Mag field} * 1000) / (n * 4 * \pi)$$

$$I = (1000 \text{ Oe} * 1000) / (21,259.84 * 4 * \pi) = 3.74 \text{ amps}$$

$$\text{Voltage} = V = I * \text{Res}_{\text{coil}}$$

$$V = (3.74 \text{ amps})(1.364 \text{ ohms}) = 5.11 \text{ volts}$$

#### Expected Strain in Terfenol Rod:

$$\text{Predicted Strain} = S = (\text{const})[(\text{mag field})(1000)/(4\pi)]$$

$$S = (2.0106 \times 10^{-8})[(1000)(1000)/(4\pi)] = 1.60 \times 10^{-3} \text{ ppm}$$

$$\text{Change in Rod Length} = \delta = L_{\text{rod}} * S$$

$$\delta = (0.5 \text{ inch})(1.60 \times 10^{-3}) = 0.0008 \text{ inches}$$

This calculation was programmed into a simple basic program to simplify the repetitive calculations. A hard copy of the code can be found in the appendix.

Based on the results of these calculations, the following coil parameters were chosen:

- ♦ Magnetic field = 1000 Oe
- ♦ Wire gauge = 30 = 0.011 inch dia
- ♦ ID of coil = 0.110 inch
- ♦ OD of coil = 0.24 inch
- ♦ No. of turns = 270
- ♦ Resistance of coil = 1.36 ohms
- ♦ Current required to achieve magnetic field = 3.74 amps
- ♦ Voltage across coil to achieve desire current = 5.11 volts
- ♦ Predicted ( $\delta$ ), or change in length), in 0.5 inch long terfenol rod = 0.008 inches

Figure 17 displays in graphic form the results of these calculations. It can be seen that as the gauge size increases, the resistance and input voltage also increase.

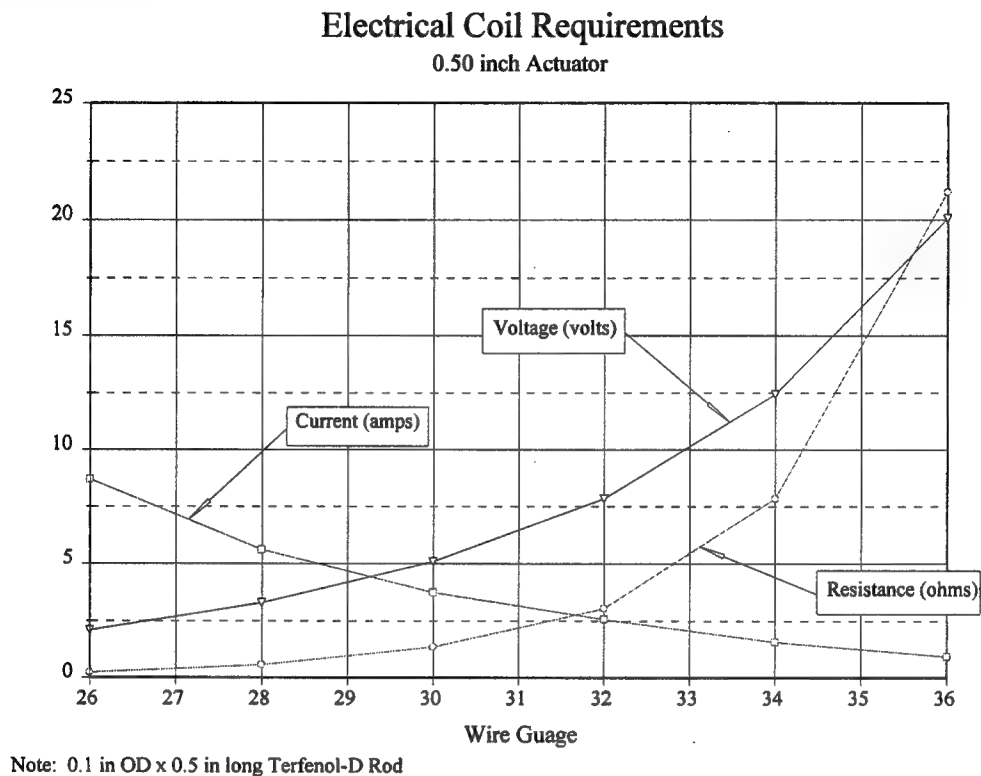


Figure 17: Electrical Coil Requirements - 1/2 inch Long Terfenol-D Rod

#### Failures:

After physical testing of the preliminary design was initialed we began to see failures of the coils due to rubbing at the ends of the Terfenol-D rods. This was expected. But occurred sooner than expected. A process of mechanically isolating the wires from the rods was developed using thin film Teflon.

Also means of potting the drive coils into the Motive Cell's was studied and would improve both the heat transfer and reduce possible solenoid bouncing within the housing.

Figure 18 illustrates the actuator design as it was at this stage of development.



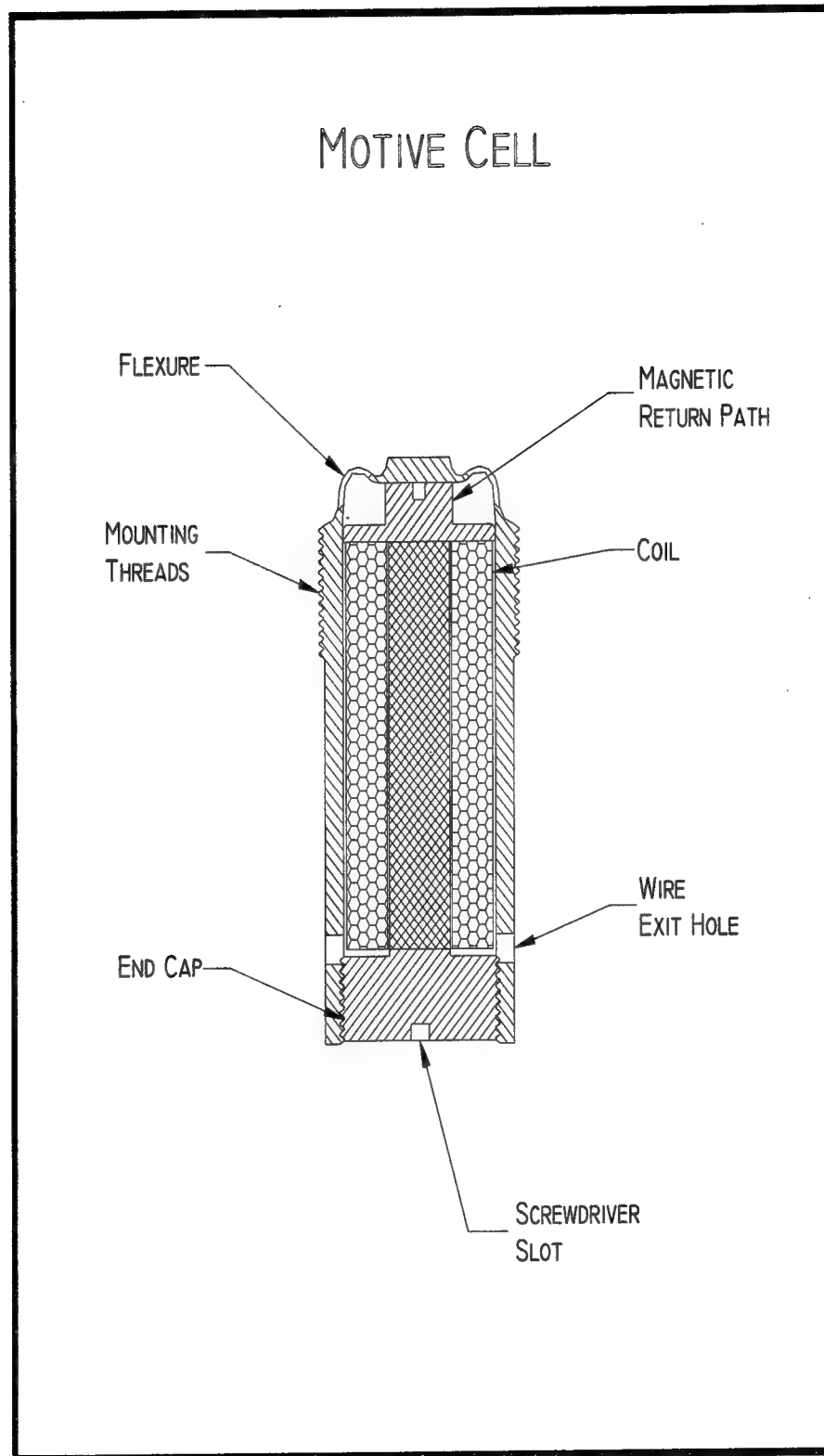


Figure 18: Initial Brake Module Actuator Design

## Motive Cell Testing

As with any design/development project, one true test of success is how well the measured performance compares to the design or predicted performance. The motive cell must demonstrate sufficient displacement for use within an inchworm type motor and not fail mechanically.

### Fatigue Life:

Determining the fatigue life of the motive cell is best determined through cycling the flexure through its range of motion for many cycles. If the flexure fails, then it did not have an infinite fatigue life. There were several motive cells constructed. Some that utilized the 0.25 inch Terfenol-D rods and some that utilized the 0.50 inch Terfenol-D rods. For a conservative estimate of how many cycles each device had been subjected to, each motive cell was operated for 30 minutes each at an average frequency of 10 KHz. This equates to  $1.8 \times 10^7$  cycles, with anything over  $10^6$  cycles indicating an infinite fatigue life. One of the early flexures failed in this fatigue test. Subsequent microscopic analysis indicates that the flexure cross-section was not close to the design specifications or dimensions. Photographs are included in this report. The other three motive cells, and subsequent ones that have been built, continue to function without signs of flexure wear.

### Frequency Response and Deflection:

The other two criteria for success were a little more difficult to ascertain. A method and device were needed that could measure extremely small deflections, on the order of 0.0001 inches, over a broad range of frequencies, from 0 Hz to 50 KHz.

The initial testing was a static test that used a digital dial indicator. This device would indicate deflection of the flexure at 0 Hz, but did not function at higher frequencies.

A second attempt to measure deflection over this broad range of frequencies was to reflect a laser off the top button of the flexure and onto a distant screen. The up and down motion of the flexure would cause the reflected light on the screen to move as well. The displacements on the screen could be calibrated with the static dial indicator test to reflect motion of the flexure.

This method had several problems. First, to obtain a significant magnification of the motion of the flexure to the light reflected onto the screen, the screen needed to be located at quite a distance away from the motive cell (i.e. 20 - 30 feet). The light that was reflected off of the flexure scattered to the extent that resolution on the screen was extremely poor. Secondly, this method would not easily indicate the frequency of the flexure deflections without developing an optical counter of some kind.

A system was then implemented using an LED / phototransistor pair. A photomicrosensor was found that provided the desired information. The chip was an OMRON EE-SG3 photomicrosensor. (Digi-Key) A sketch of its configuration can be seen in Figure 19. In this

device, the LED and the phototransistor are opposite each other and anything breaking the beam could be detected as a change in voltage.

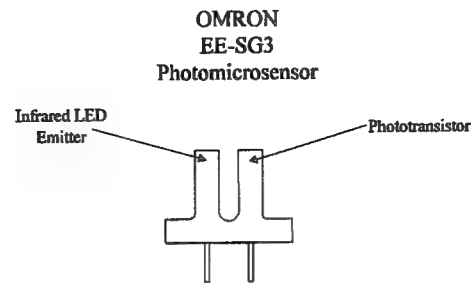


Figure 19. OMRON EE-SG3 Photomicrosensor

For this photomicrosensor to work, the motive cell needed to be modified slightly. A small, lightweight strip of aluminum was glued normal to the flexure button surface. This strip of aluminum was used to break the LED beam and register a voltage change from the phototransistor. A sketch of this arrangement can be seen in Figure 20.



Figure 20. Motive Cell with Aluminum Strip Attached.

An electronic circuit with signal amplification was needed to control the OMRON EE-SG3. This circuit schematic can be seen in Figure 21.

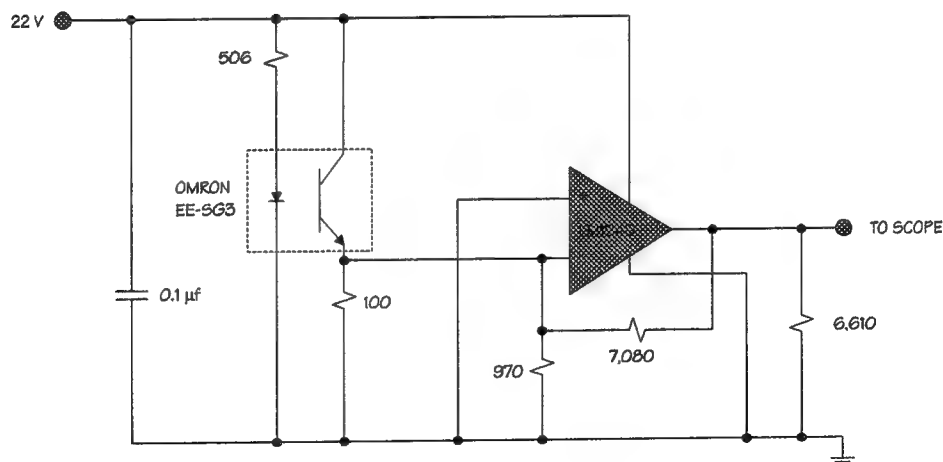


Figure 21: Driving Circuit for OMRON EE-SG3 with Signal Amplification.

### Setup and Procedure for Measuring Deflection and Frequency

The setup, which can be seen in Figure , involved sending a square wave from a function generator through a 170 Watt audio amplifier and then to the coil. A meter was used to monitor the current through the coil so as not to overheat and destroy it. In most of the characterization experiments the current was limited to 1 ampere by controlling the output voltage from the function generator and the audio amplifier. The motion of the motive cell was detected by the OMRON EE-SG3 photomicrosensor and sent to an oscilloscope where the voltages were manually recorded as a function of the driving frequency.

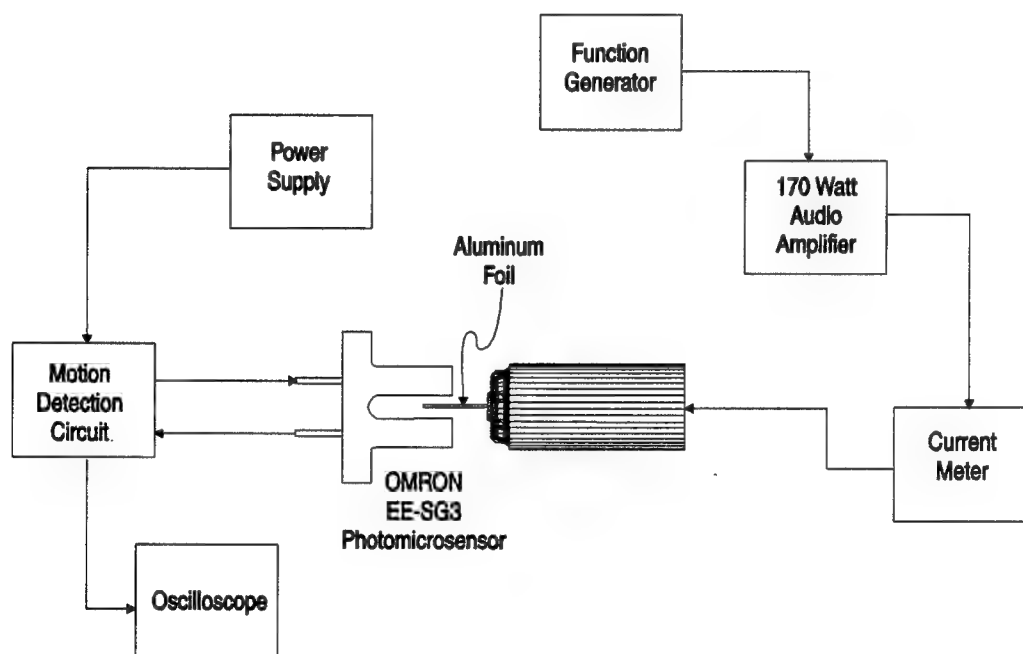


Figure 22. Setup and Apparatus

### Procedure:

To measure the displacement of the motive cells, the measurement system had to be calibrated. The motive cell to be tested was placed in a vice, with substantial mass, that was bolted onto an x-y table, which was mounted on an optical bench. The optical bench was placed on a large granite block to help damp out surrounding vibrations. The tip of the aluminum strip that had been placed on the motive cell was brought up to the OMRON EE-SG3 photomicrosensor such that the aluminum strip just broke the beam of the detector. The motive cell was then moved a measured distance into the beam of the photomicrosensor by using the x-y table. The output of the photomicrosensor circuit was directed to an oscilloscope where the displacement was measured as a voltage change. By moving the motive cell with the x-y table a measured distance, the photomicrosensor was calibrated.

For the actual frequency response measurement, the current through the motive cell was held constant over the range of frequencies by adjusting the gain on the audio amplifier and the output voltage of the function generator. The current was held constant to ensure that the magnetic field strength was constant over the range of frequencies. The frequency was swept from 20 Hz up to where the motive cell no longer responded. The amplitude of the signal from the photomicrosensor circuit was manually recorded at each frequency increment. Both of the motive cell sizes were characterized using this method. The frequency responses can be seen in Figures 23 and 24.

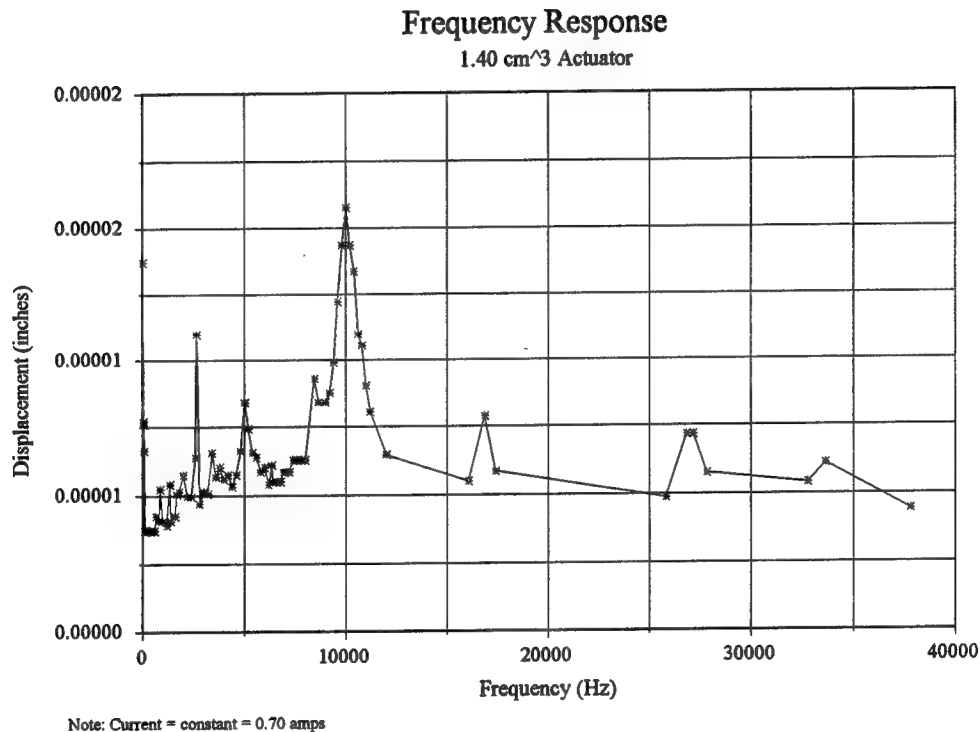


Figure 23. Frequency Response - 1.40 cm<sup>3</sup> Motive Cell

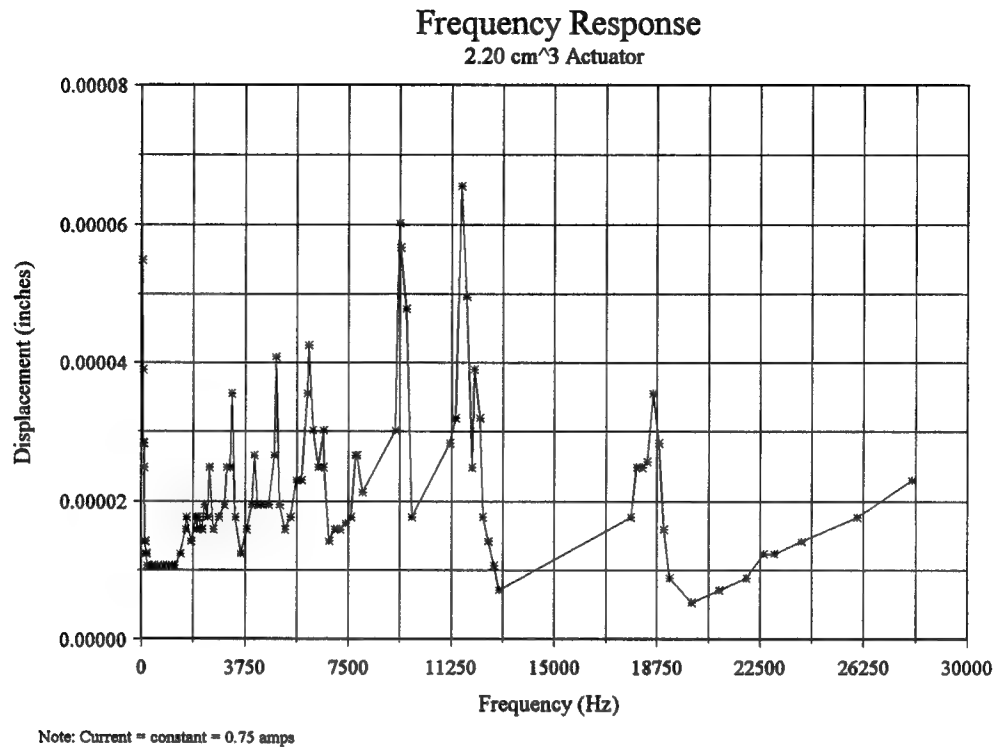


Figure 24. Frequency Response - 2.20 cm<sup>3</sup> Motive Cell

The graphs in Figures 23 and 24 show several resonant frequencies for each of the motive cell sizes. For the 1.40 cm<sup>3</sup> motive cell, the principal resonant frequency is right at 10 KHz. For the 2.20 cm<sup>3</sup> motive cell, there are a couple of resonant frequencies with one around 9 KHz and another around 13 KHz. This data indicates that the motive cells are capable of operating in the range of 5 KHz to 10 KHz as expected.

The measured displacements of the motive cells did not quite meet the predicted displacements. The results are as follows:

Table 2: Measured Displacements of Motive Cells

Motive Cell	Current	Predicted Displacement	Measured Displacement
1.40 cm <sup>3</sup>	0.70 amps	0.00007 inches	0.0000158 inches
2.20 cm <sup>3</sup>	0.75 amps	0.0001603 inches	0.000066 inches

There are many possible reasons why the predicted displacement was not achieved. First and foremost is the issue of tolerances. These motive cells were machined on a lathe by hand. It

is difficult to maintain tight tolerances on any part, but especially difficult when dealing with parts that are extremely small. This problem is demonstrated by the motive cell flexure that failed after extensive use. Microscopic analysis of the fatigue fracture indicates that it was not built to specifications. Although the other three motive cells have not failed, it is reasonable to assume that they also do not meet exact specifications. The motive cells built for final implementation in inchworm motor were to be machined by an EDM process to ensure a much tighter tolerance and improved performance.

### Maximum Flexure Frequency

One question that needed to be answered dealt with the relationship of the frequency response of the flexure to the driving frequency of the function generator. The flexure is the limiting component in this design because of its limited frequency response. At some frequency it would no longer keep up with the Terfenol-D rod. To determine this parameter, a setup similar to the one used to determine the frequency response was used. The difference was that this time the frequency of the flexure was measured off the oscilloscope and compared to the driving frequency of the function generator. The results of this study for the 0.50 inch motive cell can be seen in Figure 25. It can be seen that the flexure frequency follows the driving frequency until up around 38 KHz. This number is not unrealistic in light of the fact that ETREMA markets an motive cell that runs up to 40 KHz. (reference)

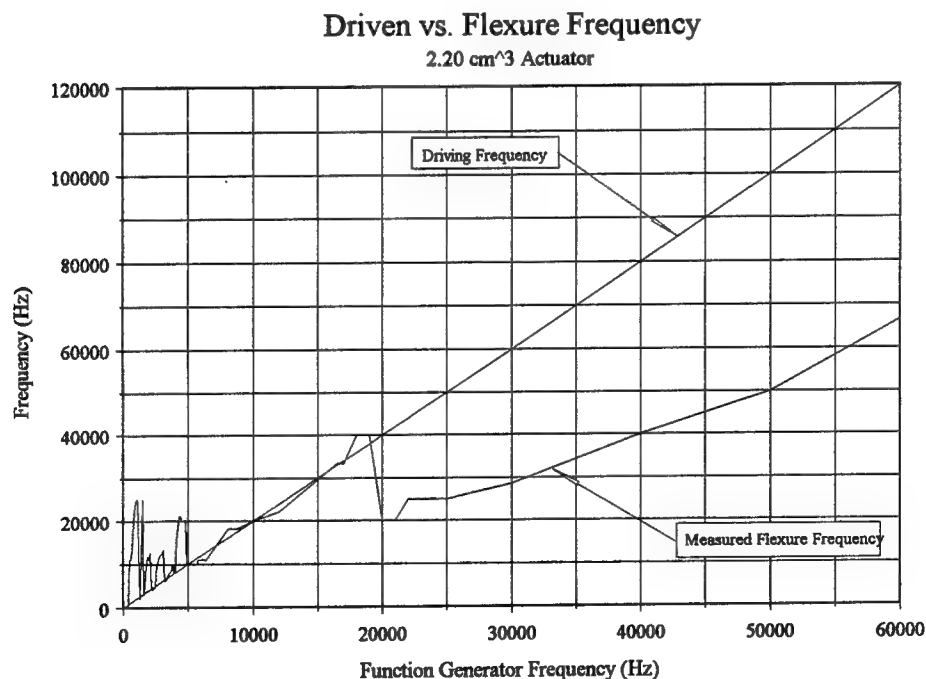


Figure 25. Measured Flexure Frequency vs. Driving Frequency

The overall concept of the Motive Cell was tested in these experiments. The data indicates that the device is a success. The device is small (about 0.375 inches long and 0.625 inches long). It provides the necessary preload to the Terfenol-D rod, and magnetic return path for the coil. The frequency response of the motive cell is within the range that would be usable for force feedback exoskeletons, and it meets the requirements set forth for an infinite fatigue life. The concept was successful but the implementation needed to be improved for the final motors. This was noted by the less than ideal motion of the Terfenol-D rods. Much of this was simply solved by using a higher precision manufacturing process. The final flexures used in the final motor have a much tighter tolerance and are machined by EDM processes. With this tighter control on geometry the predicted length excursion of the Terfenol-D rods is improved. Also we were able to reduce the hoop stresses future by modifying the slots on the flexure using the precision EDM machining.

Photographs 1 through 12 document aspects of the Motive Cell development.



### ***Progress - Task 3. Linear Motor Development***

As briefly noted in the background section of this report we ended the Phase I portion of the project by demonstrating a cigarette pack sized Terfenol-D Motor. The motor demonstrated several important features: modular design, low voltage drive, variable force output, backdrivability and digital control. Also we demonstrated that small high frequency micro movements of the motor felt similar to smooth forces. While others have demonstrated inchworm motors, most are made from piezoceramics, and are used for position control. To our knowledge no Terfenol-D inchworm motors had been demonstrated to provide a variable force. In the Phase I we demonstrated that velocity and force could be controlled either by controlling electrical current to the brake elements or varying the electrical pulsing. A combination of the two modes was possible. Variable force in pulse mode is made possible by allowing the drive shaft to move freely when no signal is applied. This allows a series of micro-pulses and non pulses to simulate a net force. Force in this sense is a combination of mass times acceleration effects and braking forces. Therefore in this application the finger tissues and exoskeletal structure integrate the many small positive and negative acceleration pulses into a sensation of a relatively smooth net force. As an alternate mode of control, if the finger is acting against a stationary object one could just lock the brakes with no pulses and just vary the amplitude of the braking force.

While Phase II was to continue and improve these preliminary studies the most fundamental questions to the project, in Phase II, were size related. No small Terfenol-D motors had been developed to our knowledge, therefore there was no preexisting knowledge base that could be tapped relative to Terfenol-D micro motors. There is quite a lot of preexisting data on piezoceramic based micro motor, but they do not have the complications of solenoid coils, magnetic return paths and various preload conditions, etc.. Also they are not backdrivable or force controllable. Conceptually the piezoceramic motors and the proposed magnetostrictive motors are similar, but their physical implementation must differ.

Clearly the device in Phase I was much too large and bulky for placement on human finger joints. Thus we began the Phase II project by evaluating several possible technologies that might facilitate making the motor smaller. There were both functional, materials science and manufacturing issues that had to be resolved. For example the smaller the structure of the motor the more important precise manufacturing technologies become an issue. Early in the project, before we had refined the concept of the motive cell we began investigating possible motor configurations and concepts. Several novel and useful concepts were designed and prototyped. Much was learned from these devices. Photographs 13 & 14 illustrate two early working concept prototypes. These devices were used to test braking methods, driving coil parameters, heating, drive methods, and drive shaft concepts. Photograph 15 shows a different approach using only one brake element. It is configured as rotary joint. This device would make a smaller motor but would have an inherently narrower operational velocity and force. But it is a good concept and should be pursued further for related application.

After we had developed a general approach that we believed would be effective we began investigating the modular Motive Cell concepts noted in the previous section of this report. Various concepts were modeled in CAD and FEA. The selection of Terfenol-D magnetostrictive rod dimensions were made after completion of the ergonomic studies related to required forced and joint velocities. Figure 26 illustrates an iteration of the inchworm motor concept.

In Phase II we wanted a force motor which had a fairly high velocity. This velocity was determined from ergonomic data on joint velocities, etc. To accomplish the target velocity it was decided to design the motor with a pusher element twice as long as the brake elements. The geometric configuration of flexure structure was also used to increase the amplitude of the linear motion.

The Terfenol-D elements for the brakes and pusher cells were chosen to be of the same diameter. The pusher element is capable of pushing approximately 45 N (10 lbf). However, because of the mechanical amplification of motion force is traded for extension and the effective net force is reduced.

The brake elements are capable of the same forces as the pusher but they have a smaller stroke. The net output force, or holding force, of the brake is reduced by the friction coefficient between the brake pads and the drive shaft ribbon. A preliminary study was conducted of possible materials which could provide adequate stiffness and a high coefficient of friction. Several novel materials were proposed and a few concepts were tested. The two most promising concepts for future development are ceramic composites technologies. A custom ceramic brake pad was fabricated by a new rapid laser prototyping system and tested. The device fabricated for this project uses hardened steel alloys for both the brake pads and drive shaft ribbon. Increasing the coefficient of friction is an area of study which will facilitate enhanced motor performance for a given size Terfenol-D rod.

The final motor developed under this contract took the final form as illustrated in Figure 27. This design was chosen over the preceding concept in figure 26, because it provided a more symmetric oscillation. Detailed engineering drawings are included in an appendix. This motor is configured using two Motive Cell modules as brakes on either end of a scissors jack type pusher element. The pusher is configured as a double flexure Motive Cell. The better the symmetry the more effective the vibration modes and hence the more efficient the motor. The basic body of the device, which encompasses the brake and the pusher elements, is a single piece flexure based design. The use of flexures reduces motion losses due to pinned type joints and also minimizes mechanical friction. The motor is fabricated using standard machining processes including surface grinding, milling, wire EDM and plunge EDM machining. The device could be relatively easily fabricated in quantity with few changes. Photographs 17 & 18 show the first finished Terfenol-D inchworm motor. The dime in the photograph is to demonstrate scale.

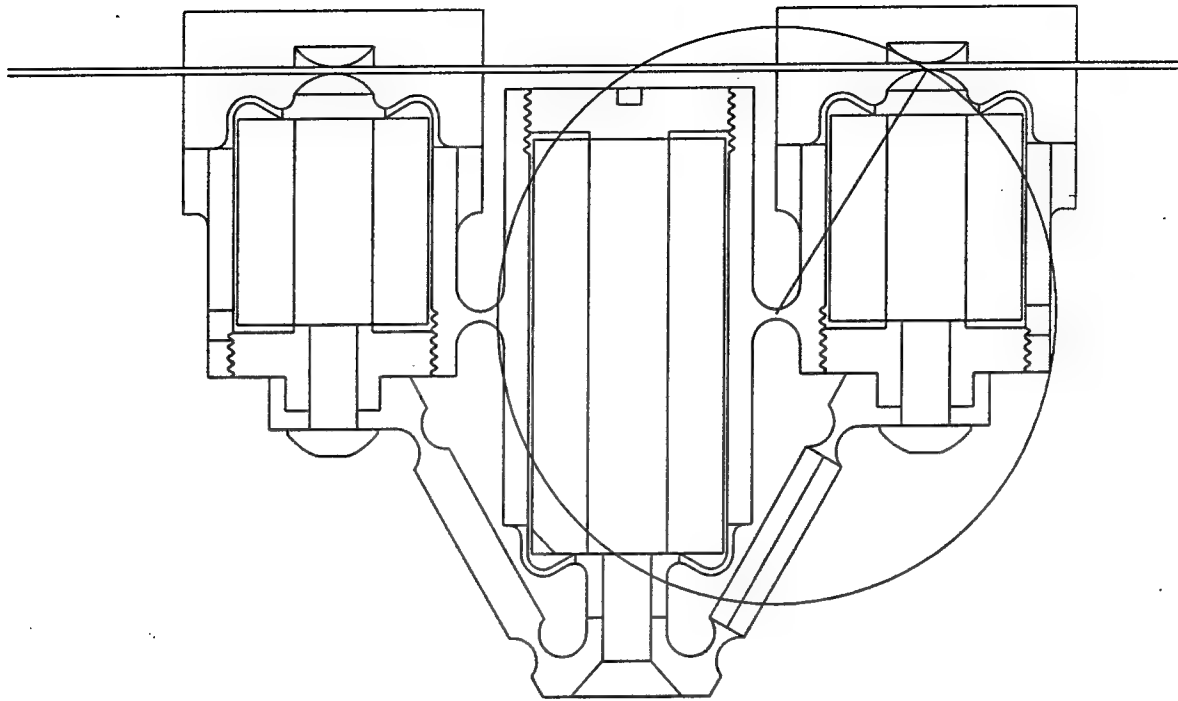


Figure 26. Inchworm concept iteration.

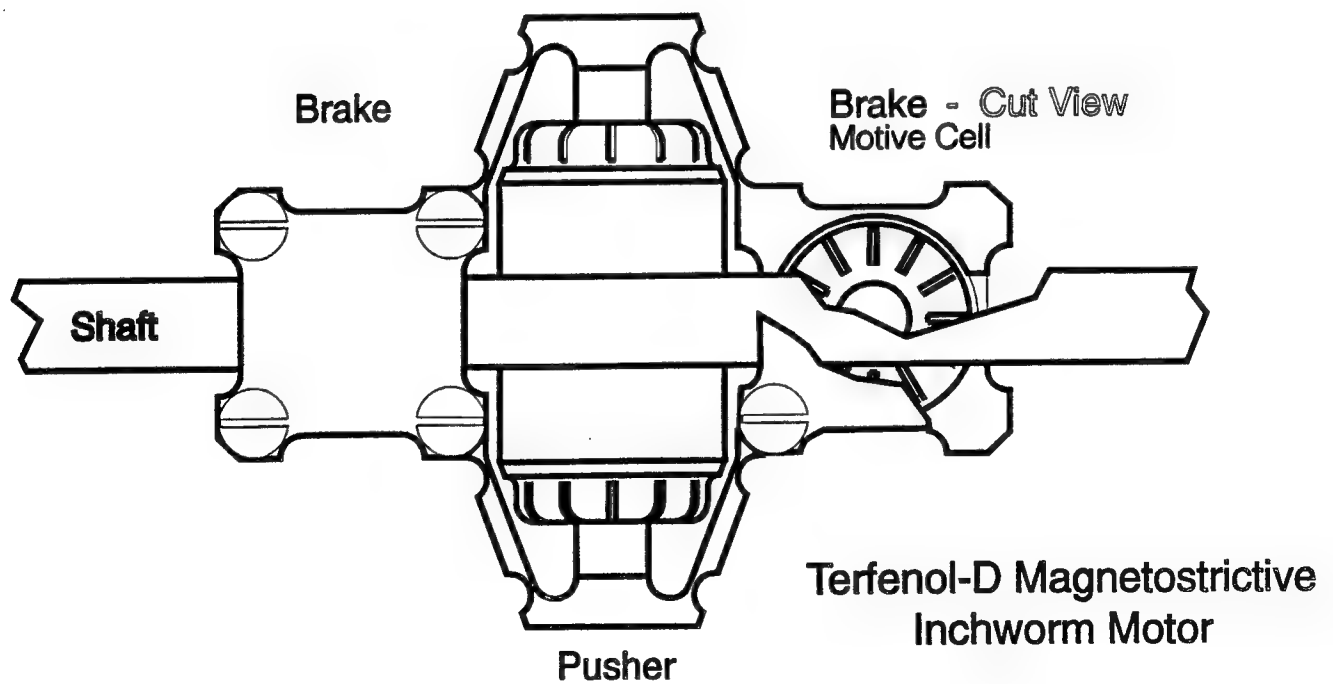


Figure 27. Final Phase II inchworm motor concept iteration.

## *Electronic Controller design*

After completion of the inchworm motor we were ready to begin evaluation and testing the prototype. In order to test the device an electronic motor controller, to provide the needed phasing, needed to be designed and fabricated.

The electronic control board (ECB) has several functions including amplification of the load cell signal and virtual force signal, offset adjustments, onboard clocking, pulse-width modulation, and driver signals for the coil driving power board. The load cell selected has a signal range from 0 to 250 mV in amplitude with an excitation of 15 Vdc. To make this a useful signal an instrumentation amplifier was used to provide a gain of 20. The virtual force signal is connected through a similar amplifier but with a lower gain setting. The advantages to using an instrumentation amplifier includes decoupling the load cell resistor bridges from circuit ground, high impedance inputs, reduction of noise (specifically 60 Hz), and high gain. Each amplifier circuit is followed by a low-pass filter (3 dB pole of ~10 Hz) to help further reduce noise and signal spikes. The conditioned signals are compared to each other to determine if the load cell voltage is higher or lower than the virtual force signal. The resultant signal controls the pulse-width modulation.

The pulse-width modulation circuit is a 16 step, digital modulator. If the load cell signal is greater than virtual force signal the pulse-width is increased. If the load cell signal is less than the virtual force the pulse-width is decreased. If the two signals are matched then there is no change in the pulse-width signal. This digital pulse-width modulator is created by using a binary up counter, a binary up/down counter, and a 4-bit comparator. The counters are adjusted once per pulse-width cycle. The frequency for the pulse-width control is about 11 kHz. This was to ensure that the pulse-width control could change from full on to full off in about 1 msec. Hence, the limiting factor on control speed is either the motors or the input filters. There is some control logic on the board to control how the brakes and pusher elements work together. This logic sets the direction of the drive shaft, the speed of the motor elements (and therefore the drive shaft), and synchronizes the braking and pushing on the drive shaft. These logic signals are used by the power board to excite the coils surrounding the Terfenol-D rods.

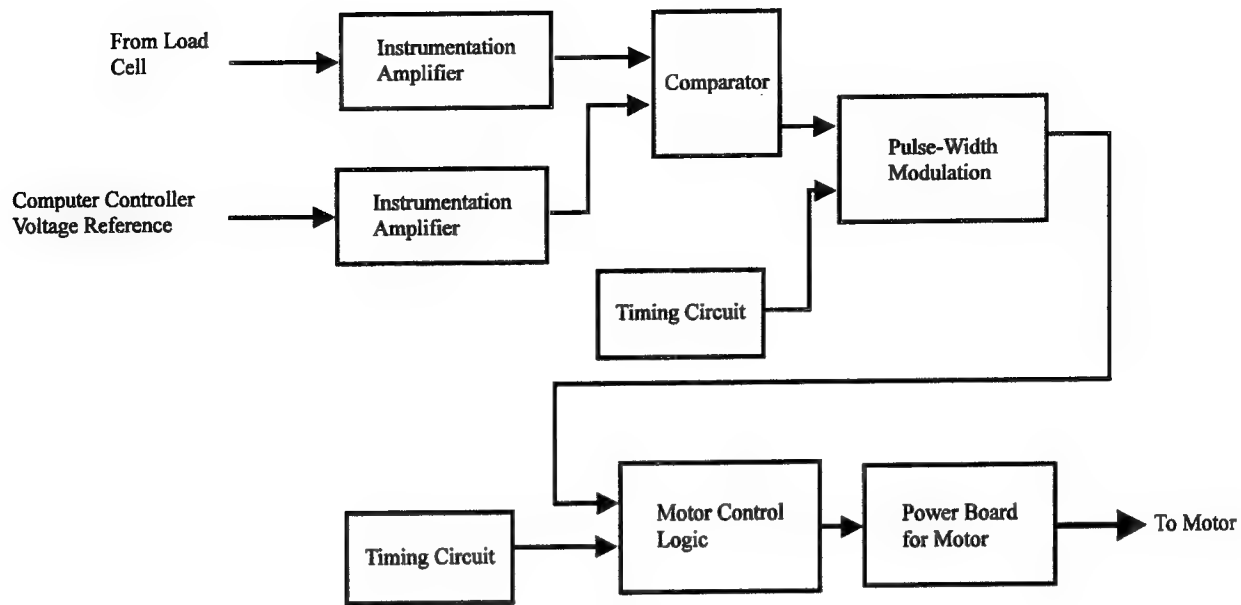


Figure 28.

### Coil Driver - Power Board

The technology for driving the magnetostrictive inchworm motor is similar to driving a brushless DC motor. It has low resistance, low voltage, and high current. The three windings are driven in a cyclic phased pattern. The inchworm motor driver is less complicated than the brushless motor drivers because we do not need to sense the position of winding relative to the magnets. In this case there is no rotor lag, the coil and the Terfenol-D are mechanically locked in position.

Several designs were considered for the power board. Initially, power modules designed for stepper motors were investigated. These modules had useful features such as combined logic and power components allowing a small package design, integrated heat sinks, and signal inputs which allowed it to be controlled from a computer. However, these modules typically could not provide a high enough current range, usually controlled only two elements, and did not allow for an adjustable time between phases. The second concept focused on using a multiple transistor power MOSFET package. This allowed for a smaller board footprint, use of logic level signals for control, and localization of heat. However, these transistor packages needed to bridge two transistors together to handle the power requirements. This meant a single chip package of four transistors could only run two drive elements. The single heat tab also proved too small of an area to allow heat sinks to effectively maintain the internal junction temperature below thermal shutdown limits. This design also prevented from using a current limiter on each individual coil. This tended to cause catastrophic failures when one coil would start to deteriorate. A custom made board was designed which allowed much easier and precise control of each coil.

Each driver element circuit contains a current limiter and a MOSFET transistor. The current limiter is to control the amount of current delivered through the wire and prevent burning out the coil. These are turned on and off by the MOSFETs. The power board uses power MOSFETs as switches for the excitation of the coils. The MOSFETs are logic level, hence they are full on with a 5 volt signal. The resistance, when the transistor is in the on state, is 0.3 ohms at 5 amps. The MOSFETs actually control the ground line. So the coils are left in a high floating state when not being used. This design allows for better control of the step response and helps keep the ground from having too much noise on it.

### Feedback Control

A commercial software package was used to demonstrate the ability of the motors and controller board for providing force feedback. This was demonstrated by controlling force with a varying position load cell and applying a varying force to a stationary position load cell. The software, Notebook Pro, is a data capture and hardware controller package. We used this software with the PC-30D data interface board. The software has built in comparator functions and can output a varying signal based on conditioned input signals. This allowed to show both force and data measurements while providing a reference voltage signal. This control board was used in collecting the initial arbitrary force control data which follows.

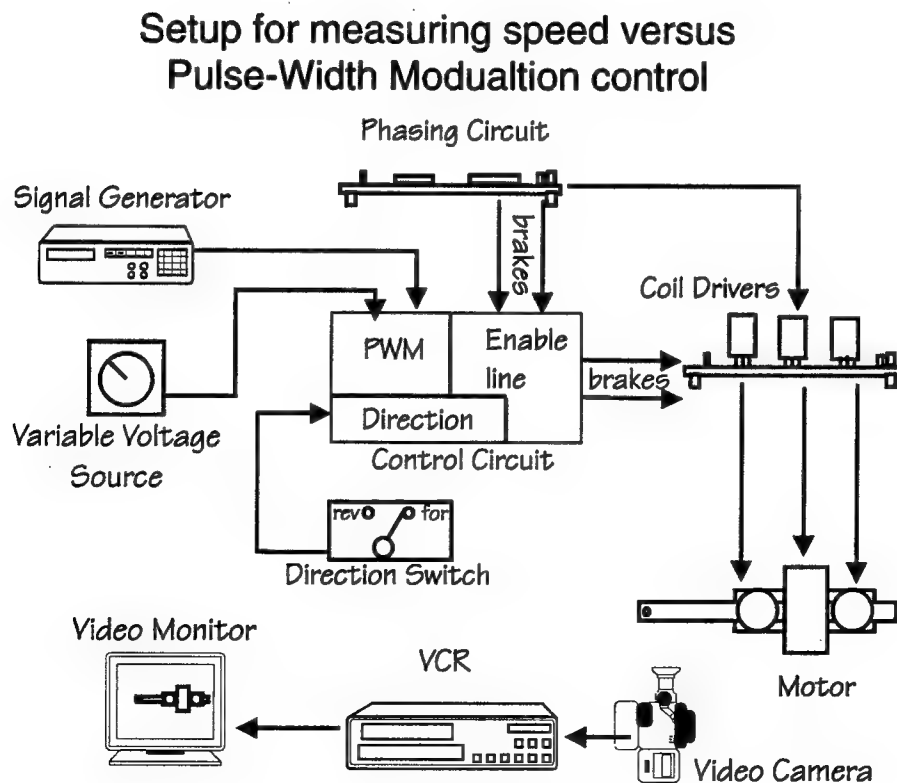


Figure 29.

### *Terfenol-D prototype inchworm motor - evaluation and testing.*

#### *Two Element Experiments - Inertial Drive Method*

During this period of the project we also investigated several driving methods. Of particular interest were experiments conducted to evaluate the possibility of two element driving methods. This is an inertial drive system. In this method only one brake element is powered and the other is disconnected. Unlike the traditional inchworm method, the motor does not climb along the shaft. In the two element mode the motor effectively grabs the shaft and propels it forward. The drive shaft is grabbed thrown forward, released and re-grabbed 5000 times per second. The motor worked very well in this mode. It was demonstrated slightly lower force and velocity outputs. The advantage of this demonstrated inertial drive concept is that we can design a Terfenol-D motor with one third the volume and weight with a simple change to the design (take a hack saw and remove the unused brake motive cell). Because of the very limited scope of the project the concept was demonstrated but has been not pursued further at this time.

#### *Three Element Experiments - Inch Worm Drive Method*

Preliminary experiments to test frequency response and force output capabilities were conducted using calibrated spring scales. Velocities were measured by videotaping the motor motion under varying conditions and the velocities were measured from the TV screen.

The motor was found to be highly controllable. The output velocity was shown to be fundamentally a function of the number of steps per time. The inchworm motors velocity peaked at approximately 5 KHz. This was due to a resonant mode of the bulk motor frame. Above this frequency the motor continues to function but the velocity is degraded due to the non-resonant condition and perhaps an overlap of the mechanical and electrical phases.

Switching from forward to reverse was instantaneous and is accomplished by simply switching the pulse sequence to the motor. That is to say, the direction of motion is controlled by selecting which (Motive Cell brake) element leads in the pulse train.

#### *Testing fixture.*

In order to facilitate the measurement of motor force and arbitrary force control it became necessary to construct a special calibratable testing fixture. The test fixture needed to provide a known motion (velocity) output and an electrical feedback signal from a load cell to the controlling computer.

The test fixture was designed and constructed as shown in photographs 19 and 20. The apparatus provides a linear motion generator. The linear motion is sinusoidal and has a high mechanical impedance. The following figure illustrates the setup of the experiments.

## Setup for applying a varying force to a stationary object & constant force to a moving object

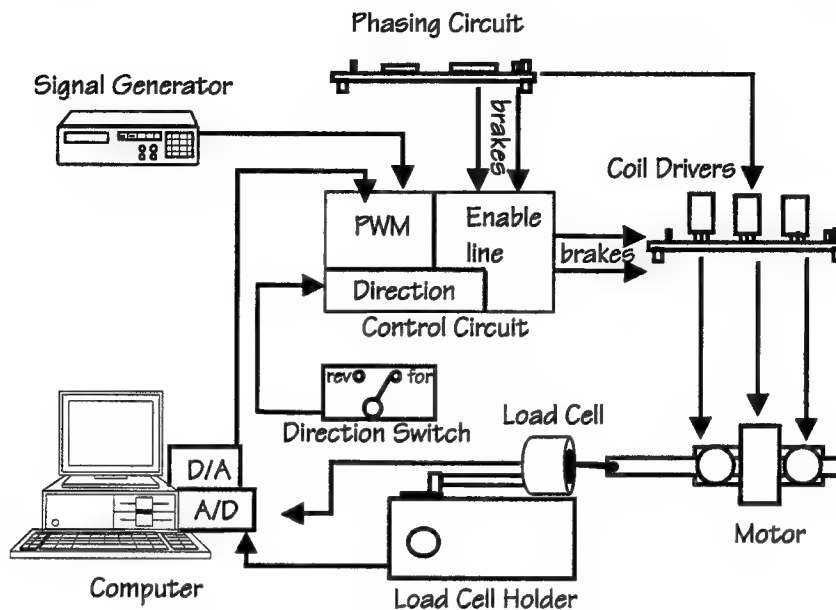


Figure 30.

The maximum force measured was 10 N (2.25 lbf). The maximum is obtained when the Motive Cell is adjusted intimately with the drive shaft. Because of a small variation in the original motor drive shaft ribbon thickness the velocity was improve when a small gap was allowed between the shaft and the brake. If the gap between the drive shaft of the motor and the Motive cell is opened to much it produces a reduced force output, since some of the energy is used to extend the Terfenol-D with no clamping. For most of the experiments we operated the motor at less than the maximum force condition.

The maximum velocity measured was 14.5 cm/sec at approximately 5 KHz. This corresponds to an average inchworm step of 0.029 mm.

As currently configured the range of motion is only limited by the length of the drive shaft selected. The motor was tested with a shaft 15 cm in length.

The following data is presented in graph form. As a matter of interest the first graph is a plot of a human finger being used to try and provide a constant force on the slowly moving load cell which is on the moving shaft of the test bed. In addition to the use of force sensing in the hand the human subject was also provided a visual feedback voltage on a CRT to aid in force tracking. The data is instructive when compared to the rudimentary control system used on the Terfenol-D inchworm motor.



# Human Control

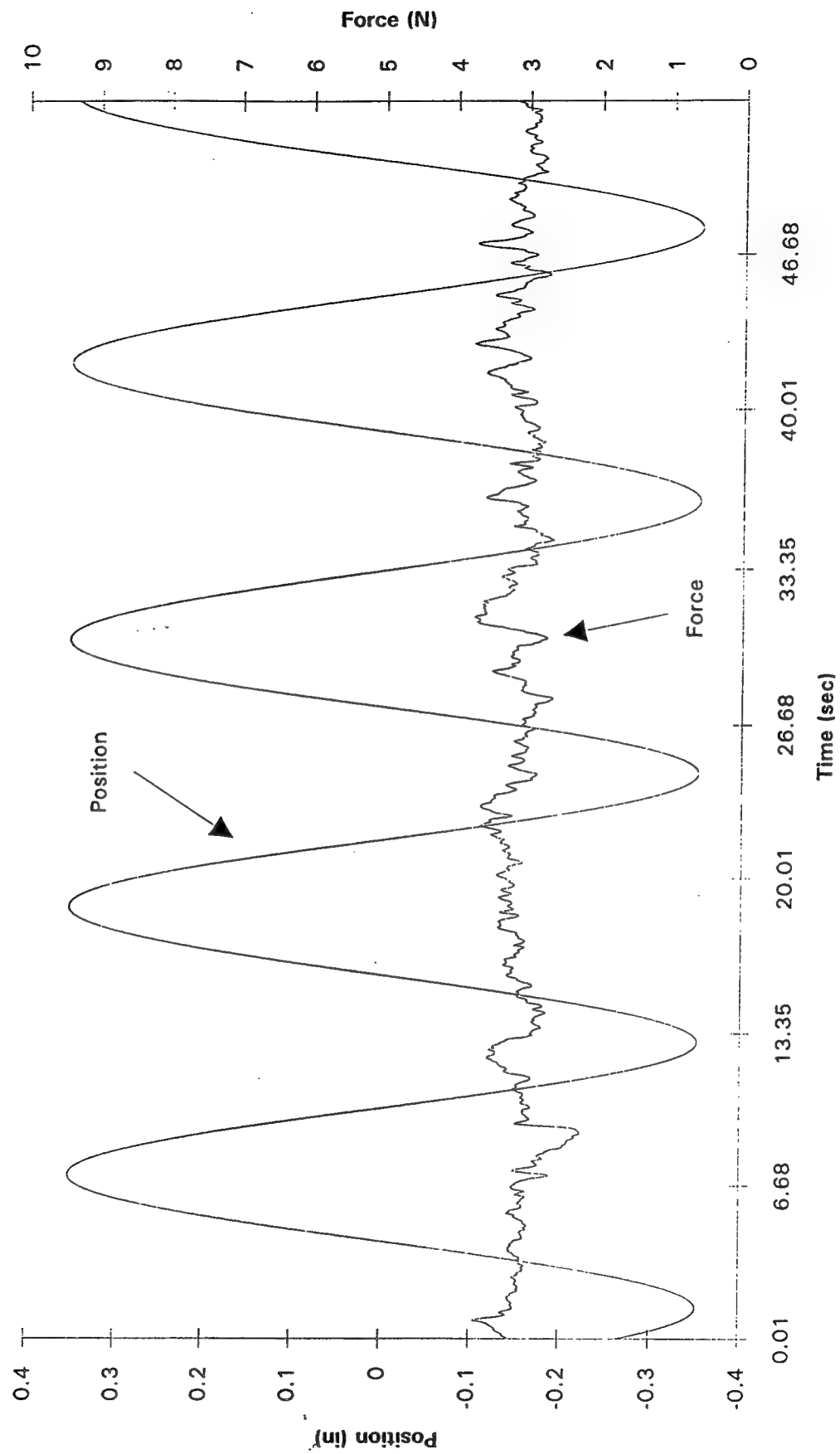


Figure 31. Human finger providing constant force tracking on a moving object.

# Varying Position with Constant Force

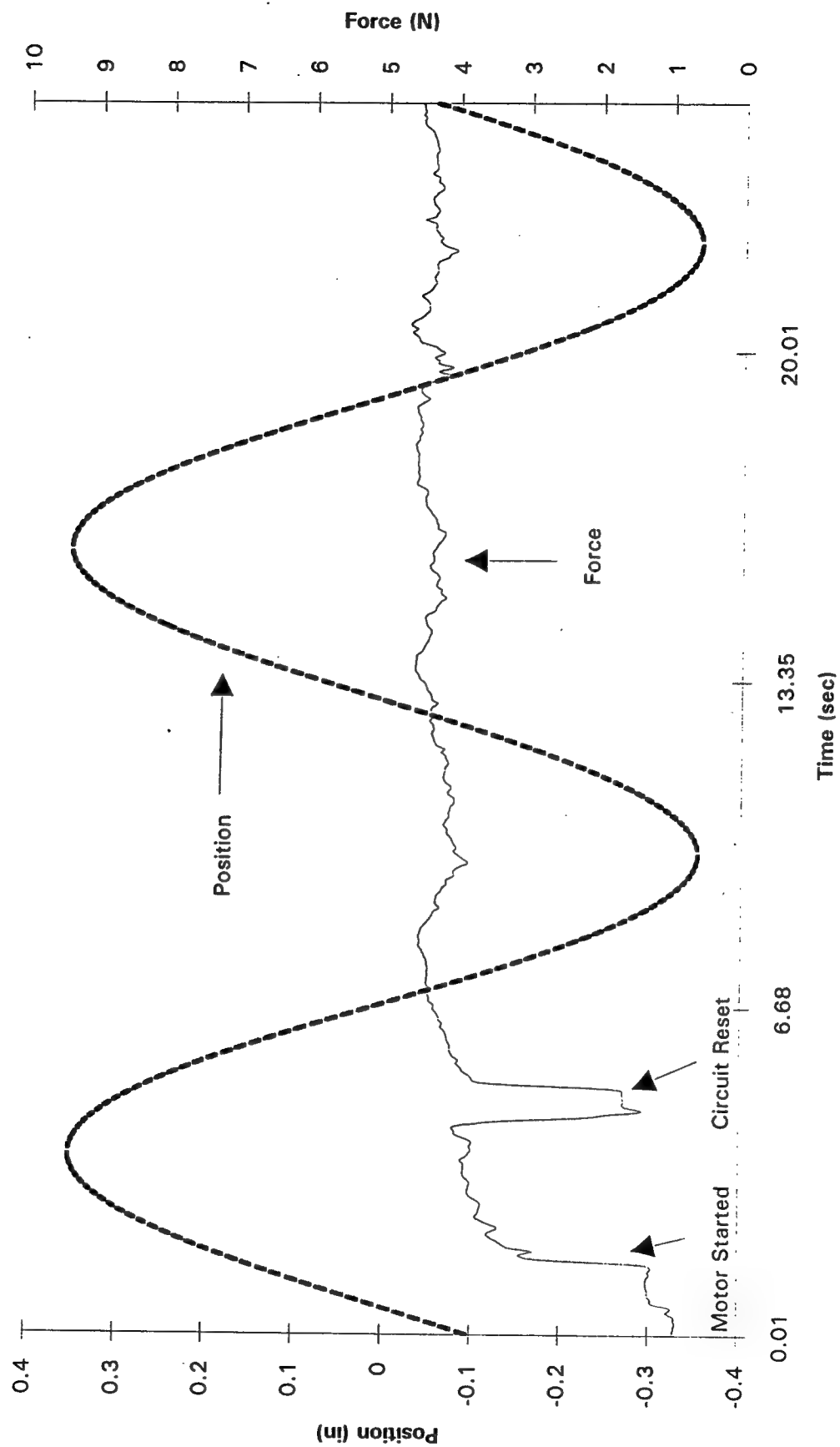


Figure 32. Terfenol-D motor providing constant force tracking on a moving object.

# Varying Position with Constant Force

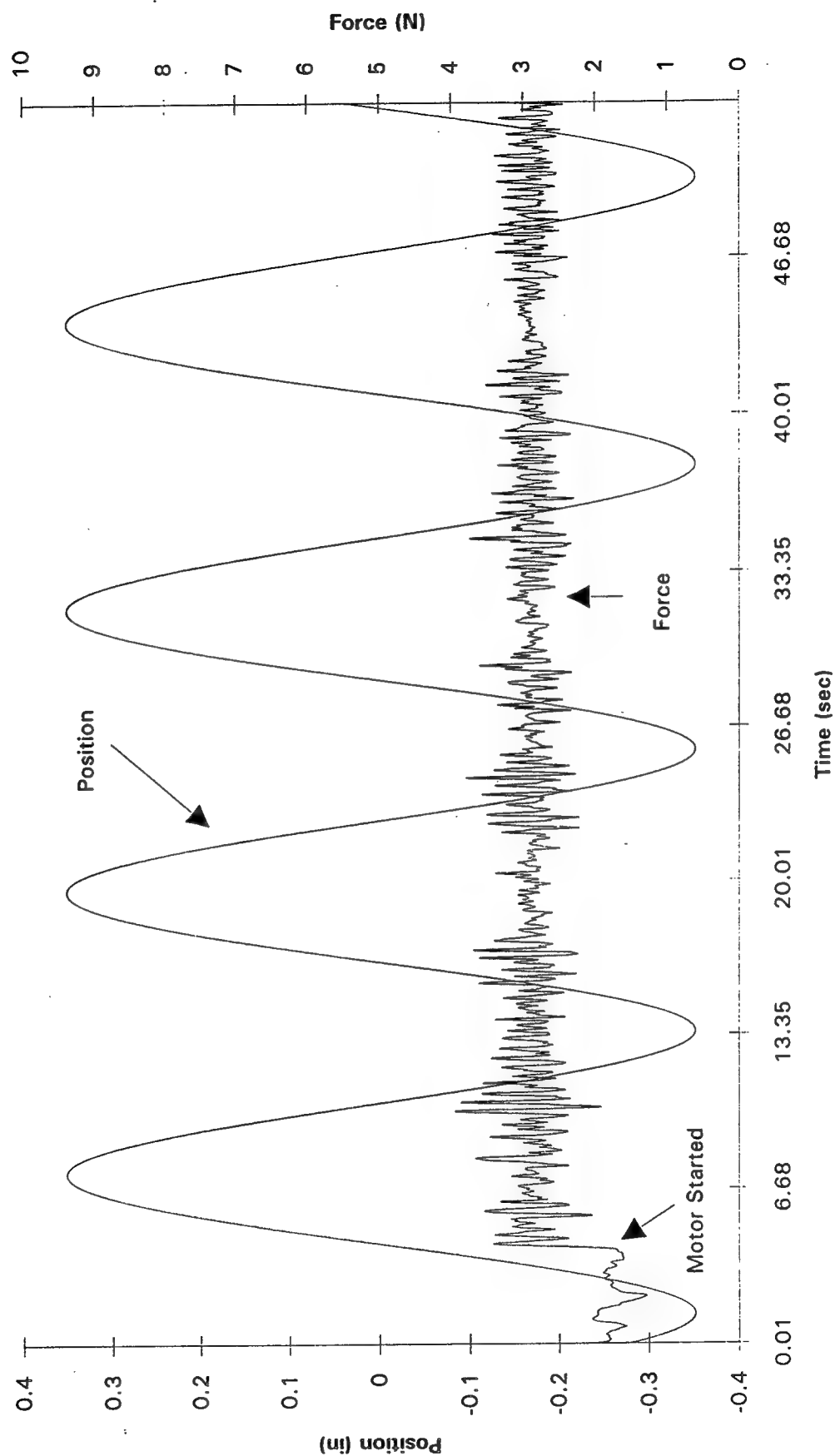


Figure 33. Terfenol-D motor providing constant force tracking on a moving object.

# Stationary Object

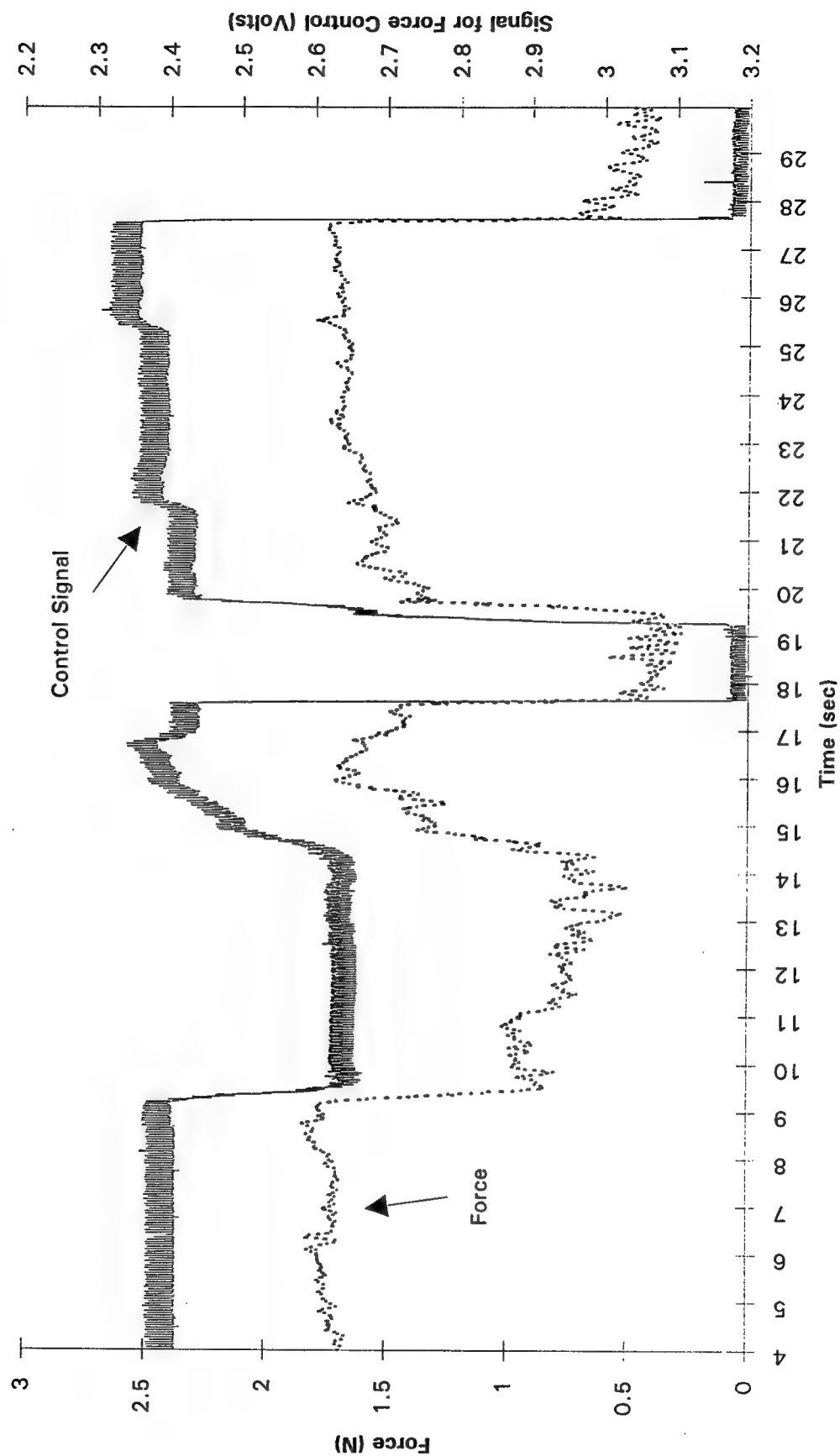


Figure 34. Terfenol-D motor providing varying force on a stationary object.

Stationary Object

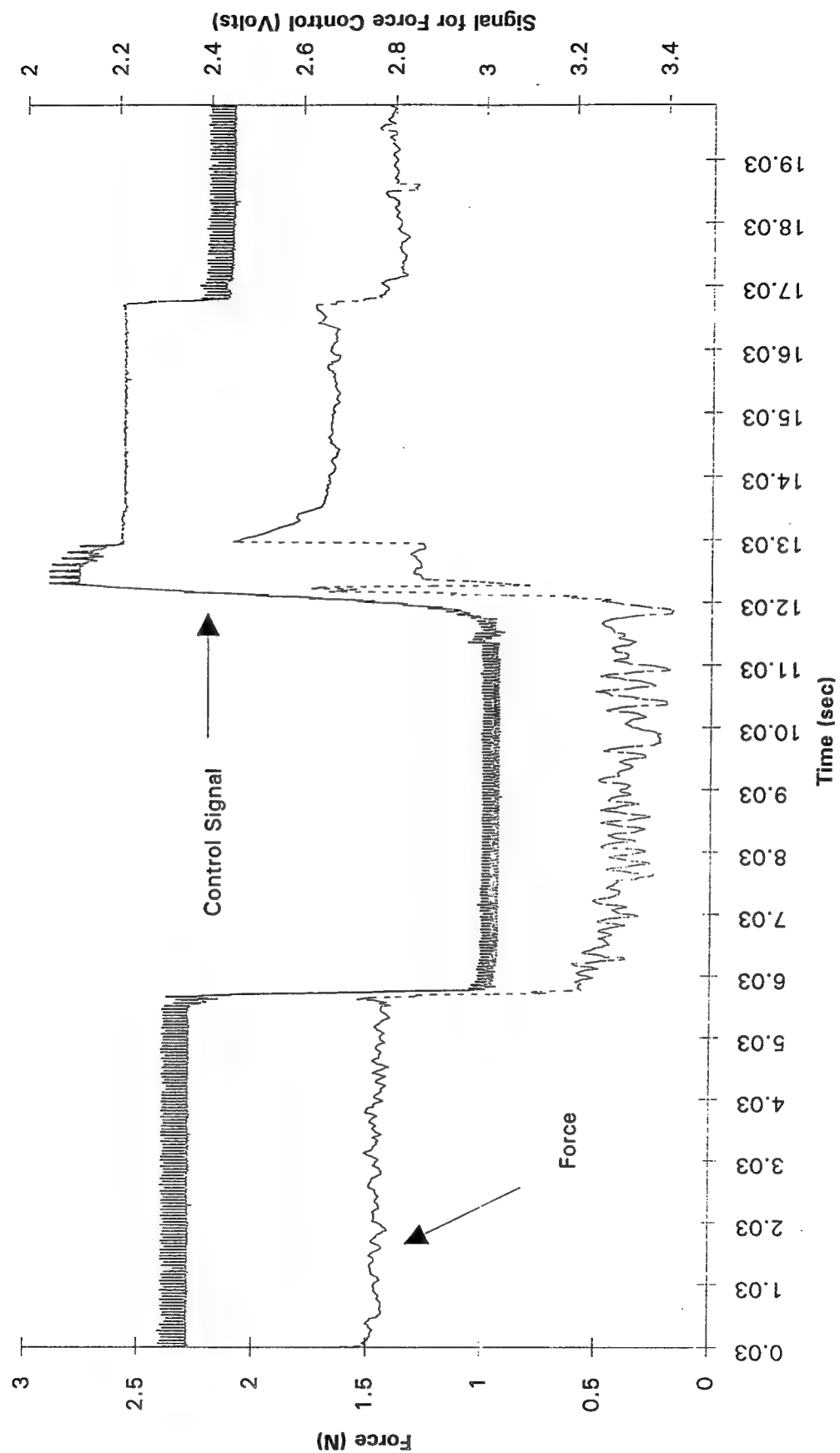


Figure 35. Terfenol-D motor providing varying force on a stationary object.

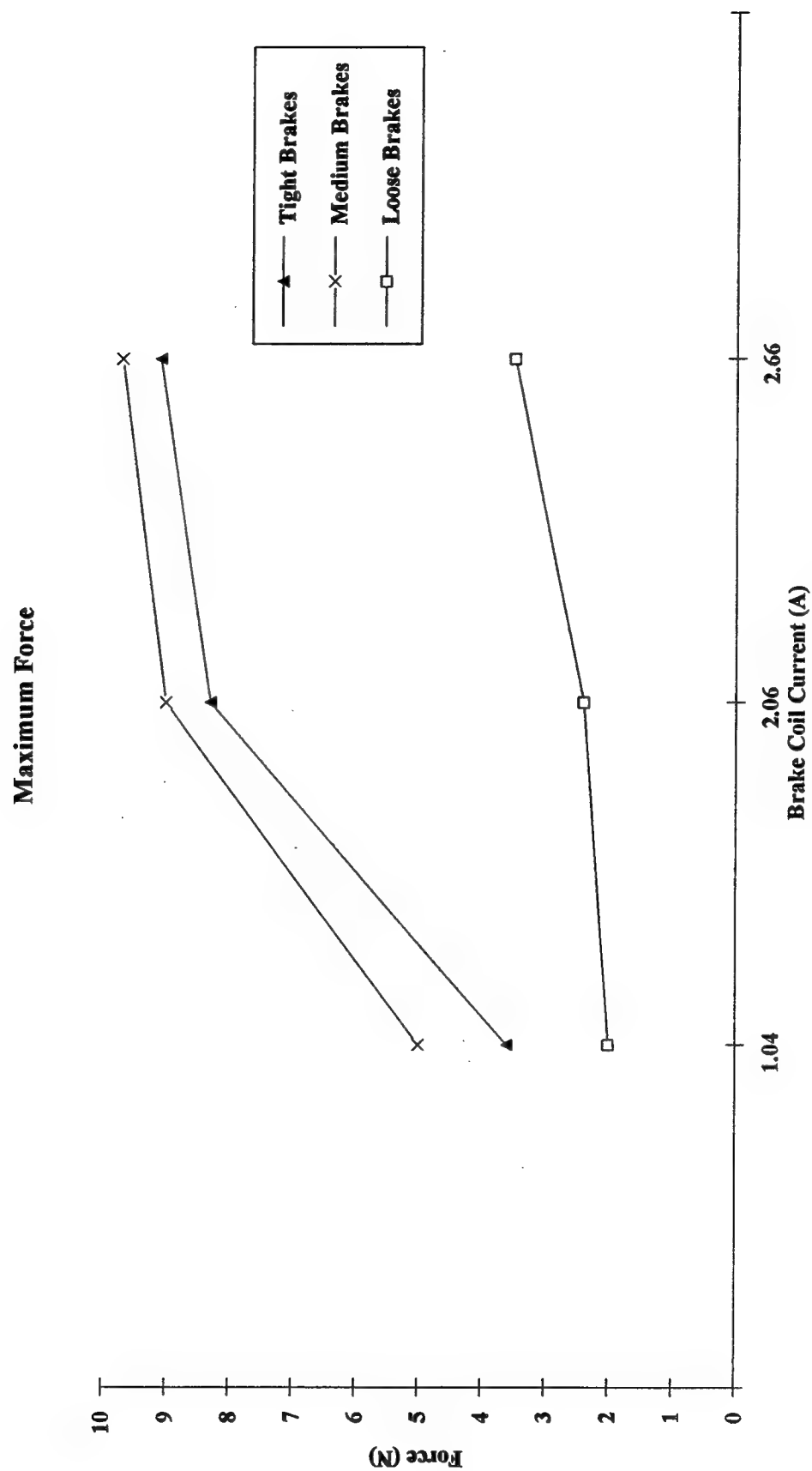


Figure 36. Maximum Force measurements as a function of current and brake adjustments.

Maximum speed (01/27/95)

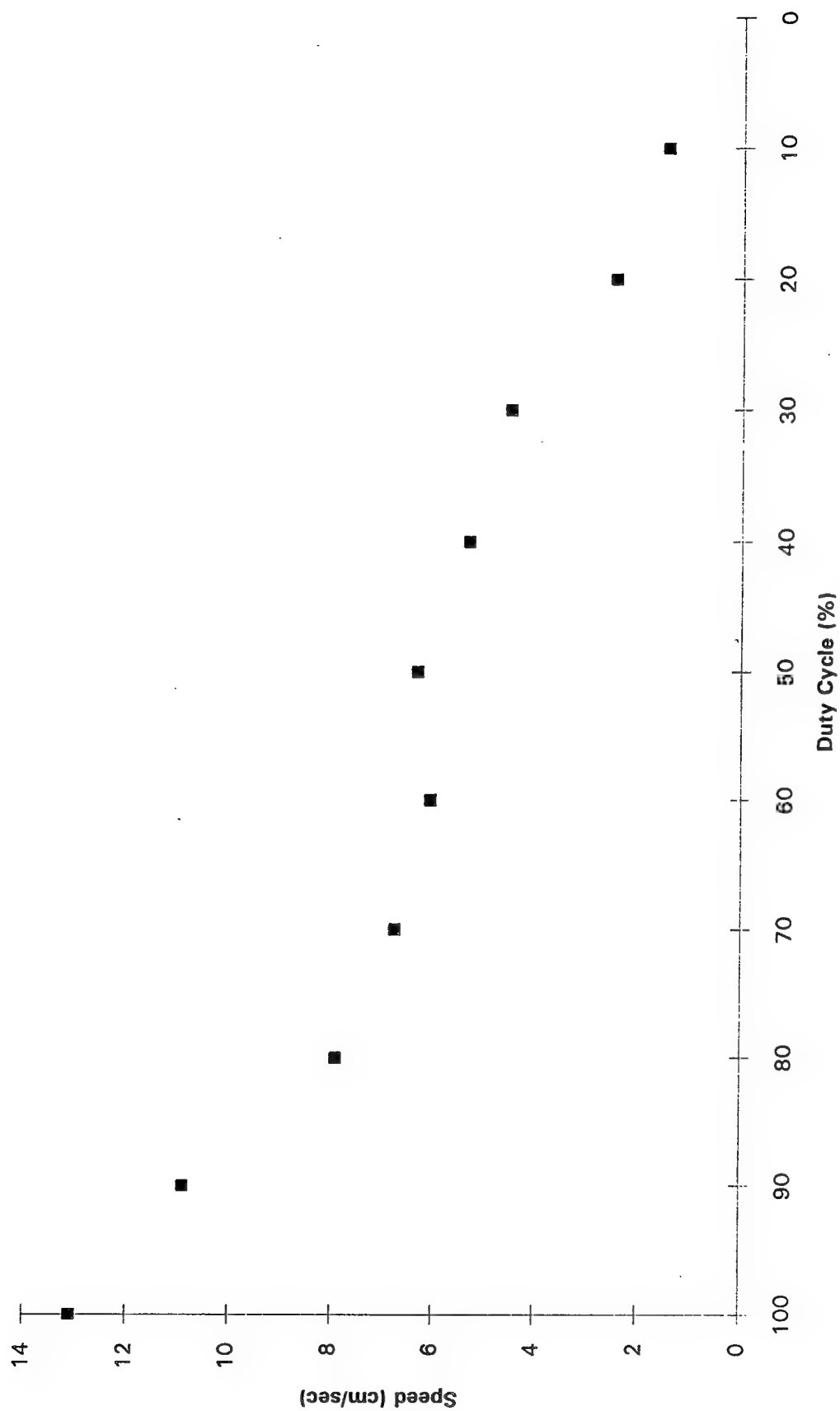


Figure 37. Speed versus pulse width modulation at 5 kHz.

#### ***Progress - Task 4. Application Simulation***

The objective of task 4 was to explore methods for the application of the new actuator for dexterous force feedback. Or in other words, to integrate the actuator into a dexterous exoskeleton. It was understood from the beginning of the project that the motor developed in this project would be a beginning and that further improvements to the actuator would come as future funding was made available to this or other research teams. Thus, given that we are implementing a less than perfect actuator, the exoskeleton can certainly be improved as the motor improves. The integration of this actuator as it currently exists into an exoskeletal device is meant to be a demonstration of future possibilities rather than a demonstration of limitations. The limitations are however noted at the end of this section and serve a useful purpose in mapping out the direction of needed future development. The author believes that the obvious limitations of this system, such as noise, load sensors, etc., can be improved significantly given reasonable study and development.

During the course of the project we have studied an assortment of issues related to the ergonomic constraints for force feedback and exoskeletal attachment. We came to this task with certain blind spots and preconceived biases. The literature on the subject has also formed biases as to which ergonomic issues are of most critical concern. One of the most fundamental issues related to force feedback is whether this feedback is best given to the human interface in the form of, what we refer to as, "virtual object force feedback" or as an "exoskeletal feedback". Solutions for these types of mechanisms tend to evolve differently. Both concepts need new methods, actuators and concepts. The virtual type force feedback concepts are less concerned with the control of a slave telerobot and are therefore are potentially more simple to implement. The PHANTOM device is a good example of a virtual object feedback. The P.I. has developed a theoretical bias towards the virtual type devices for most applications, but was contractually constraint to pursue the exoskeletal master slave type controller concepts. Clearly there is a need for exoskeletal configurations, but there may be a larger commercial demand for the virtual object systems. It has been anticipated that the need for force feedback exoskeletons is especially critical where the device is to be used as a controller for an anthropomorphic dexterous slave robot. As the technology now stands there is no one specific slave robot hand master in mind for this application, therefore the solutions for the exoskeleton master are general in nature.

During the project several discovery prototypes were fabricated to help us elucidate various design requirements for joint freedom, size and force application methods. One of the concerns which first shadowed our attention was that of the somewhat complex motion of the hand. Much of this concern is in fact unfounded if one begins to think properly about the concept of exoskeletal tracking. The concern grows from reading too much into the study of human joint motion. Much of the literature is concerned with replicating the exact motion of the bone joint with the goal of making prosthetic joints. We are concerned with a much simpler case of tracking the motion of the exterior hand positions and not the exact motion of the bones. We can not conveniently attach to the bones. The exoskeletal tracking case can be and is a much simpler case compared to bone tracking. There is much room for improvement in this area. This exoskeletal case is much simpler because we are constrained to interface not with the human bone, but with a significantly compliant human tissue bed surrounding the bones. If the tissue is



used to absorb the small variations in movement in joint axes, it can be shown that simple pin joints can be used to model the hand motion inside the exoskeleton. In the short term it is unlikely that we will have slave robotic hands in a variety of sizes. The human hand (of various sizes) inside a master exoskeleton is used to position a (fixed size) slave. Therefore at this point we are designing an exoskeleton which is adjustable for many size hands with no particular need to match to any specific robot hand. It is reasonable to believe that slave hands can be designed with pinned joints and that the exoskeletons should have the same pinned geometry. This is also true for the thumb joints. A good fit and tracking can be achieved with four axis per digit. There is also a move toward less degree's of freedom per digit such as in work on geared fingers by NASA, etc. The prototype devices shown in the photographs were used to convince ourselves about the adequacy of fixed axis pinned joints as an exoskeletal interface to all joints in the hand. In this project we have tested several different concepts to identify key issues. The following photographs and figures illustrate some of this devices.

The issue of hand size variation amongst potential users has also been given much consideration. The final device we have chosen to fabricate is adjustable for hand size in a multitude of ways. The device adjusts for finger thickness, joint length and joint position. The device is not perfect however and will not fit very small hands well. We have developed a highly adjustable device. This is however probably the wrong approach to take if one were developing a commercially viable system for average consumers. This is because adjustability leads to excessive complexity and cost. It is also likely that for a viable consumer product one might evolve towards a partially adjustable system. More simply, if volume were sufficient and cost was low enough, personal exoskeletons in small, medium and large might be practical. The concept of "one sizes fits all" usually equates to "one size fits almost no one well".

Another difficulty in the implementation of our final prototype was the size of the load cell. We did not have adequate time and funding to design and implement a new or custom small force sensor into the system. Thus the bottom of the finger rings are unnecessarily thick. This is not generally a problem except it can dramatically limit the curling of the fingers into a tight fist position. This is especially true when the joints are adjusted close together for small hands.

### *Angle Sensing*

Angle sensors adequately small were not located in our search of commercial supplies which would work in this application. Hall sensor devices such as used by the EXOS are small but have inadequate angle sensing range. Also we had some trepidation about the use of these devices because of possible magnetic interference from the yet undesigned magnetostrictive motors. Slotted type encoders were not felt to be precise enough for this device since they are not capable of measuring very fine motions such as tactile like responses. They are also significantly large. One of the significant problems with small profile tactile sensors using PVF2, is that they have a very poor low frequency response. We would like low frequency compatible devices in order to facilitate measurement of human frequency tactile signals, i.e. 0 to 300 Hz. Therefore we developed a new angle sensor for this project to give us fine resolution, small size, and wide frequency response (0 Hz to High - Mechanical limits).

TRA's technology utilizes a novel means of measuring angular position. It involves the optical polarization phenomena that occurs with transverse electromagnetic waves. Non polarized electromagnetic waves have multiple orientations. However, an electromagnetic wave having displacements in only one direction is said to be linearly polarized. Polarization of light is generally accomplished with the use of a polarizing filter. When two polarizers are used in series, the relative polarization angles of the films determine the intensity of the light transmitted. The amount of light transmitted through two polarizing films can be determined by the following relationship:

$$I = I_{\max} \cos^2 \theta$$

where:

- $I_{\max}$  = maximum intensity of light transmitted
- $\theta$  = relative angle between two polarizing films
- $I$  = intensity of light transmitted at angle  $\theta$

With this relationship, when the polarization angles of the two films are parallel to each other, (i.e.  $\theta = 0$ ), then the intensity of the light transmitted is equal to  $I_{\max}$ . When the polarization angles of the two films are perpendicular to each other, (i.e.  $\theta = 90$ ), then the intensity of the light transmitted is equal to zero. A graphic representation of this relationship can be seen in Figure 1. Here  $\theta$ , or the relative polarization angles between the two films is represented along the "X" axis and the light intensity is represented along the "Y" axis. It can be seen that as the films are rotated  $90^\circ$  with respect to each other the intensity of light transmitted goes to zero.

To increase the usable angle of the sensor we can add a second pair of detectors at and use a simple mathematical manipulation to linearize and extend the useful sensing range.

TRA has built several prototypes (see photographs) based on this cross polarization principal. The technology is based on measuring the change in light amplitude relative to the motion of a simple polarize film. The concept was implemented in a very small geometry and was implemented in a stand alone configuration as in Photograph 26, and imbedded into a motorized finger joint, as in Photograph 27, and imbedded into the final demonstration device in Photograph 35.

### *Load Cell*

During the course of the project we were not able to locate any off the shelf miniature load cells which would satisfy our needs. The two best devices evaluated were a strain gage, and a thin film device. We tested the Uniforce device and felt that it would make the better sensor for this application. None of the available configurations were of the appropriate geometry for the project, and were not easily modifiable. Therefore we opted to buy standard strain gauge

modules. The strain gage load cells are much too bulky for the application, and the strain gauge technologies do not generally integrate well in a commercial, cost sensitive applications.

Load cells for the final device were purchased from A.L. Design, Inc. 1411 Military Rd. Buffalo, New York. The Model ALD-SP-MICRO. They have a capacity of 10 lbs with a safe overload equal to 150% of the rated capacity, and a ultimate overload equal to 250% of rated capacity. The load cells are strain gage based devices.

#### *Final Electronic Control Board*

A revised board was developed for the final demonstration and added a few improvements over the initial design (noted in the previous section). A directional jumper was added to allow for changing the direction that the motor runs. A second comparator was added to provide a high and low force determination. This comparator compares a voltage reference, set with a potentiometer, with the compensated signal from the load cell. The output from the comparator is used by the power board to vary how hard the pusher element contracts. The instrumentation amplifier was modified to adjust for a different load cell. The new load cell signal ranges from 0 to 20 mV with an excitation of 10 Vdc. Hence, the amplifier gain was boosted to 200.

#### *Final Power Board*

The only revision to this circuit was the addition of a 5 Vdc relay and a second power resistor. The relay is controlled by the high/low force signal from the controller board. The relay places a second power resistor in parallel with one used by the current limiter in the pusher element circuit. This effectively provides a higher current to the coil, which causes the terfenol to push harder. This is possible with the pusher element since it is twice as large as the rods used in the braking elements.

#### *Software Force Feedback Control*

The commercial software package has been replaced with a custom designed, graphical interface control program. The code is written in Microsoft Quick C. The software simulates a three jointed finger segments. These are scaled to be approximately the same relative lengths as a human index finger. The angle between the simulated segments are determined by capturing the voltage signal from the TRA angle sensors. These signals are then converted into a number useful to the program. The software also simulates a square object on the screen. The object can be moved to various points on the screen. The object has been designed to simulate a harder force the deeper a finger segment penetrates. This demonstrates the ability to simulate different degrees of reaction forces.

The software uses calls that are specific to the PC-30D interface board. However, the code can be altered by changing the commented lines where a different set of board commands would need to be placed. This allows for different interface boards to be used. The only requirements is that the interface board contains three analog to digital input lines and three

digital to analog output lines. Command controls are described in the manual under the software section.

### *Software*

The software and a simple instruction manual are provided in an appendix. The software is only rudimentary. It is used as an engineering tool for study and is not intended as a user friendly commercial interface. Better software is not really indicated at this point in the development and should be developed in concert with a more refined Phase III implementation.

The software is designed to read in a signal from the angle sensor and display a three segment finger. The angles between the adjacent segments will mimic the angle read by the angle sensors. The angle sensor outputs a voltage which is a function of its angular position. These signals are read by an analog-to-digital interface board and inputted into the software.

The screen will also display a square, movable object on the screen. The software will register any collision between the finger segments and the square. If contact is detected the system will output a virtual force signal (via a digital-to-analog interface board) to the TRA's electronic control board. The level of the output signal will be determined by the depth at which the finger segment penetrates the square.

#### Control Keys:

Up Arrow: Moves the virtual object towards the top of the screen.

Down Arrow: Moves the virtual object towards the bottom of the screen.

Left Arrow: Moves the virtual object towards the left.

Right Arrow: Moves the virtual object towards the right.

0 (Zero): Activates/Deactivates the virtual object.

Esc or 'q': Quits the program.

### *Finger interface*

To accommodate a large number of hand sizes and geometry's we developed system which is comprised of an adjustable ring and a sliding rails. The rings are configured as u-shaped rings which are slotted on the sides to allow tightening. We have provided three different u-ring sizes. This will fit most individuals. The slots on the sides of the u-rings interface with a plate which is on the top or dorsal side of the fingers. This plate is provided with two female dove tail slots. These slots interface with corresponding male dove tails on the virtual joint and inchworm motor assemblies. By moving the virtual joint assemble relative to the finger plate on is able to adjust the finger length and joint possition. This system is quite adaptable. But with adaptability comes complexity and adjusting the system to fit one hand is tedious but necessary to provide non binding motion of the joints. If the joint axis of the finger is not properly aligned a moment is produced on the virtual pivot and this increases friction.

Significant limitation is caused by using the large load cells. These require a larger than necessary u-ring geometry.

### *Wire routing*

We have not addressed the issue of wiring of the exoskeleton to any significant extent. Each joint on the finger has 6 wires from the motor, 4 from the angle sensor and 4 from the strain gage load cells. This makes a total of 14 separate wires for one joint or 42 for the three joints on this prototype. Just combining grounds would reduce this count to 30.

### *Exoskeleton Joints*

There are numerous concepts which have been proposed and or tested to measure finger joint position and or provide force feedback. During this project we have also investigated several possible configurations that would be compatible with the motor we were developing. They are namely: Fixed Axis Joint Concepts, Multi - Axis Joint Concepts, Congruent Axis Joint Concepts, Fixed Axis - Slider Joint Concepts and Virtual Axis Joints.

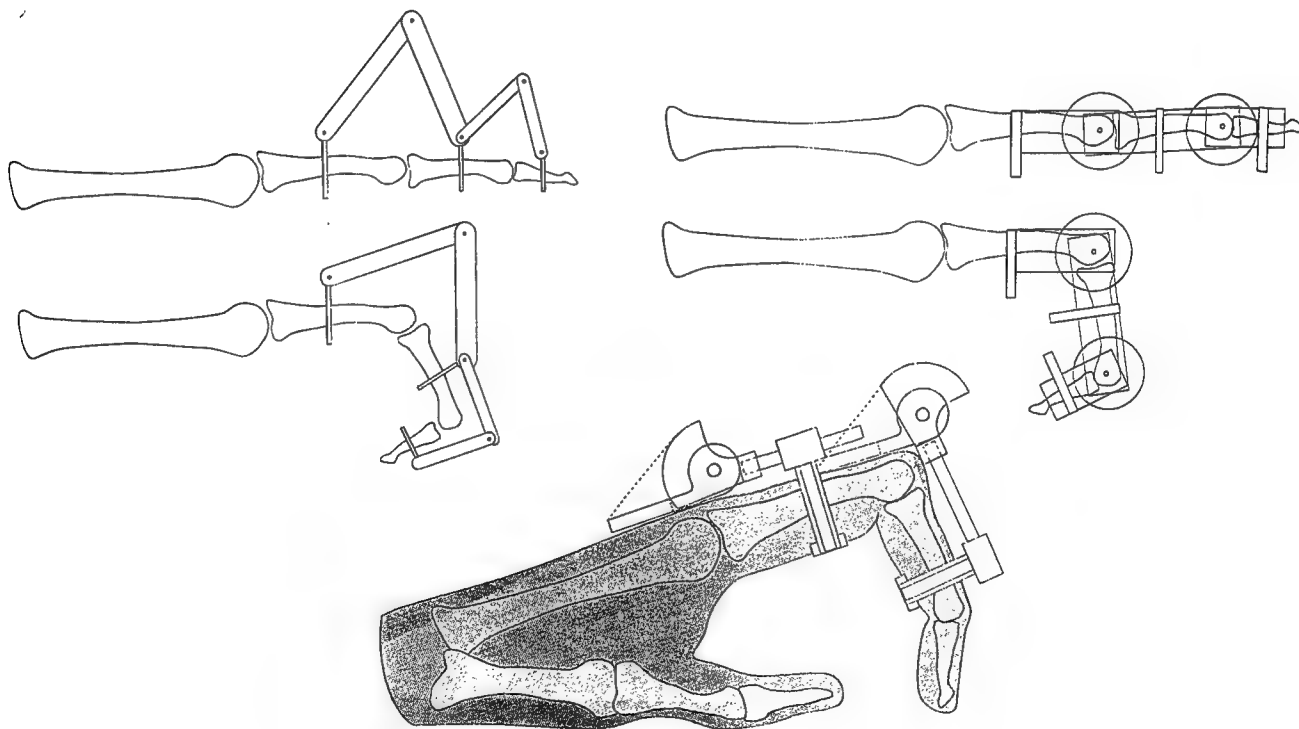


Figure 38. Exoskeleton joint concepts.

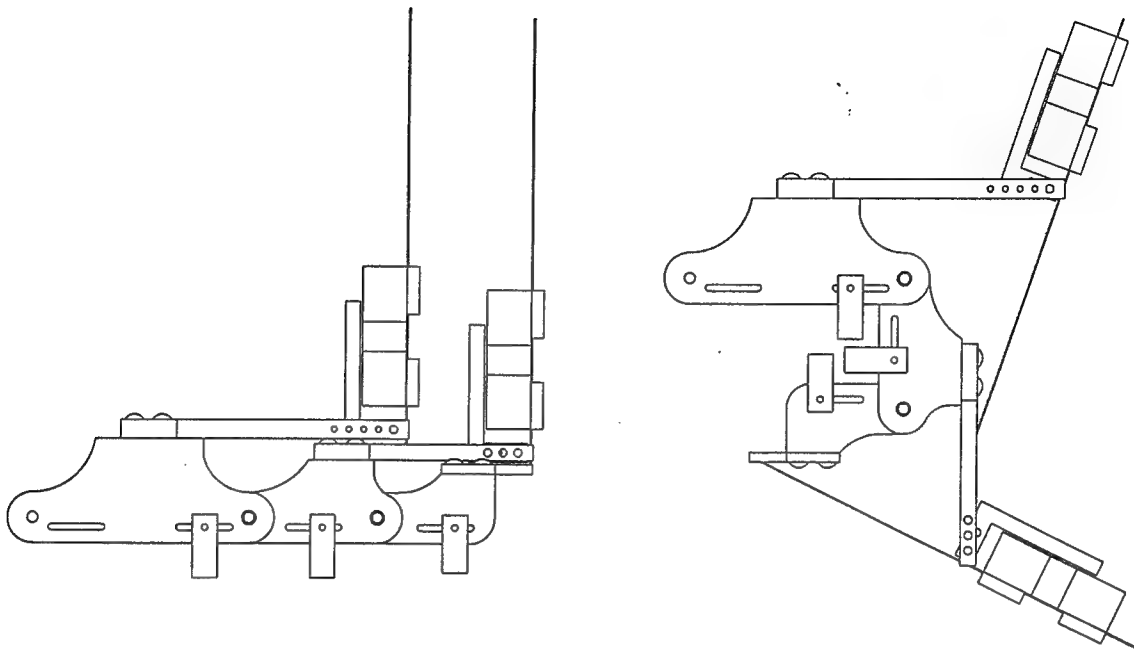


Figure 39. Pinned configuration with motor in marionette location.

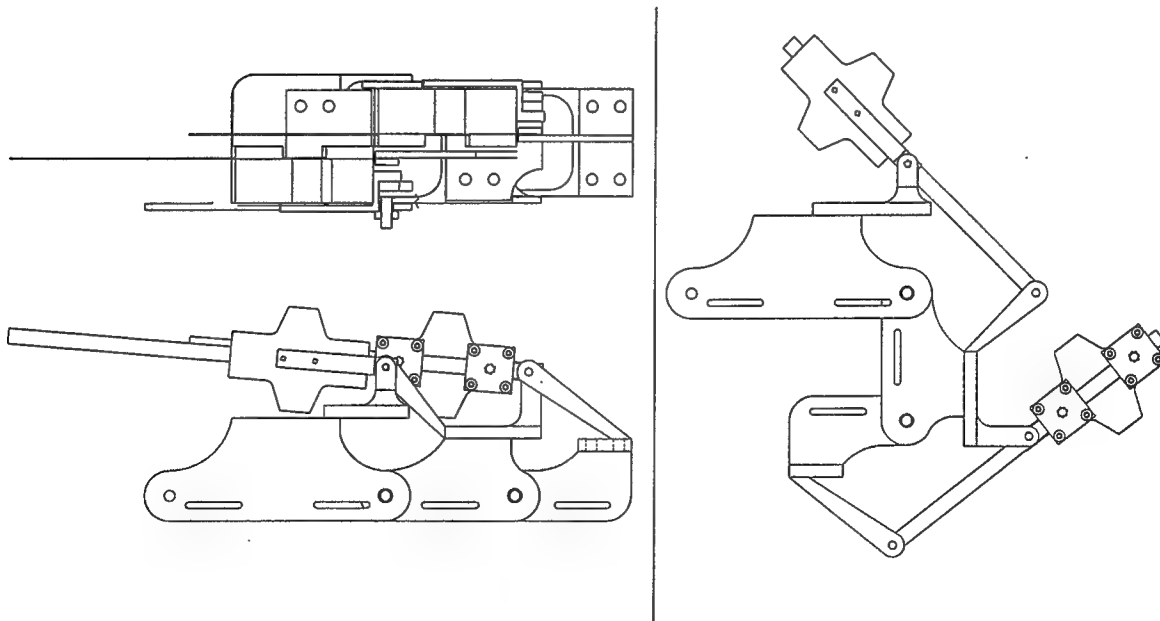
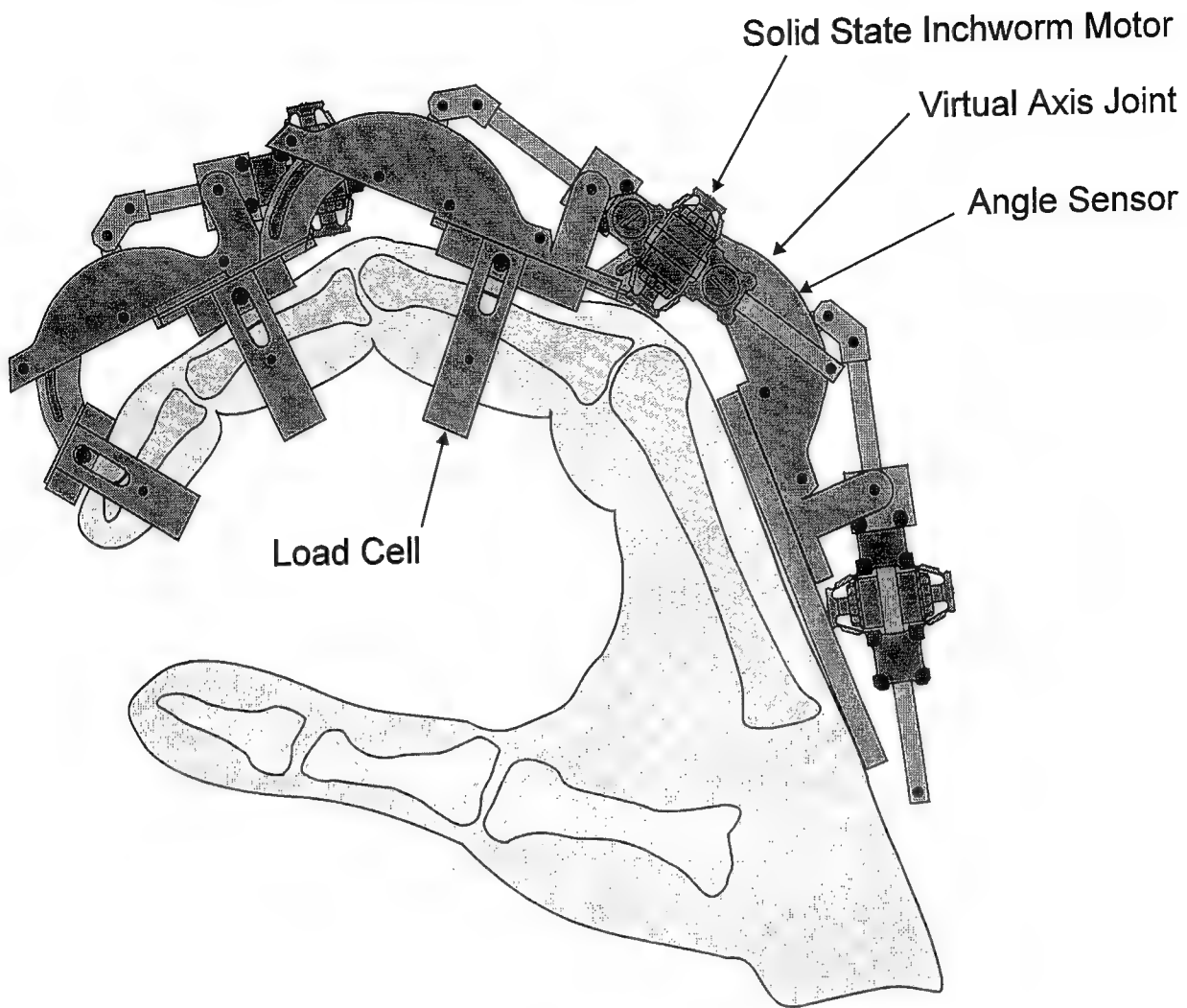


Figure 40. Pinned configuration with motor in parallel location.



## Terfenol-D Force Feedback Handmaster

Figure 41. Virtual Joint Configuration.

### *Final Integration*

In our evaluation of the pro's and con's of the pinned and virtual joint configurations, noted in the figures above, it was decided that both would be prototyped and evaluated. The major advantage of the pinned configuration is its ability to accommodate a wide range of hand sizes without a need for significant adjustment. Its main disadvantage has to do with the thickness of the finger attachments and associated angle sensing. This becomes a real problem if multifingered configurations are envisioned. In our final effort during this project we have decided to integrate the inchworm motor with the Virtual Axis Joint concepts. Figure 41 illustrates the final exoskeleton device concept. The figure in the user manual itemizes each component.

The virtual joint concept, while not yet fully refined, has several important long range advantages.

- ♦ It minimizes the amount of structure on the sides and back of the fingers.

By minimizing structure on the sides, and inside of the fingers we provide the capability of performing closed fist grasping.

- ♦ It is adjustable to fit various finger lengths.

The virtual joint concepts facilitates the placement of sliding rails for adjustment which are non obtrusive to grasping motions.

- ♦ It is a ridged structure.

The ridged structure is important for precise measurement of joint angles and control of either virtual, or slave robotic applications.

- ♦ It facilitates integration of the angle sensing methods, polarizer, slotted encoder or others.

A polarize angle sensor is embedded into the virtual joint configuration and does not add to the size of the device. The concept would also be directly compatible with a slotted encoder embedded in the same fashion.

- ♦ It is compatible with Phase III integration of the motor into the virtual pivot.

With the virtual joint configuration it is proposed that Terfenol-D type inchworm motor could be directly embedded into the virtual joint. This could easily be accomplished by having the motor inchworm its way along the virtual arc rather than as independent motor. The arc of the virtual joint would replace the ribbon drive shaft and the motor would be embedded into the existing arc housing structure. This would be a very compact, light weight and capable configuration.

The final prototype was fabricated in-house using a combination of Delrin plastic and Aluminum. This makes for a very light weight finger. Photograph 34 shows an exploded assembly view of all the components needed to assemble one joint. Photograph 35 shows the virtual pivot finger near completion with the Terfenol-D inchworm motors attached. The finger has three actuated degrees of freedom and one nonactive degree.

### ***Progress - Task 5. Documentation***

During the course of the project the progress achieved was documented. Included in the Appendices are engineering drawings for the project. The project also produced this final report, 7 quarterly reports, and two technically detailed presentations for the Air Force technical monitors.



## ♦ Problems for Future Improvement ♦

At this point in the development of Terfenol-D inchworm motors we have identified and provided engineering solutions to a number of problems to get to the state of the art as it is. However some engineering problems and opportunities have not been resolved or implemented in the current device. These problems are implementation or engineering related. At this point we have not hit up against any of the physically inherent limitations of the Terfenol-D material. This means that significant strides in performance can be expected without heroic efforts or breakthroughs in material properties, though the Terfenol-D materials are improving. As an example when this project began the literature related to Terfenol-D had shown eddy current limitations around 8 kHz. This was subsequently shown to be a false assumption. Currently commercial Terfenol-D actuators are for sale with flat mechanical responses exceeding 40 kHz (ETREMA, Inc.). The US Navy also continues to push this envelop. Laminated structures will certainly raise this higher.

In this section of the report problems are identified and presented in list form. Accompanying each known problem are some suggested solutions or directions. The list is in two sections though the topics are not exclusive. The first relating to the magnetostrictive motors and the second to the exoskeletal issues.

### Problem areas and concepts and methods for their solution.

#### Inchworm motor.

##### Noise at 5 kHz

Noise is indicative of both the resonant frequency of the structure and mechanical energy losses in the system.

Solved by:

Increasing frequency above audible.

Smaller size reduces acoustic air coupling

Higher frequencies couple less well to air

Eliminate mechanical slapping

Strategic use of shielding, damping

Harmonic dissipation

##### Waste heat from coils.

Effects efficiency, undesirable thermal expansion, burn out.

Solved by:

Shaped Pulsed signals (non-square),

Reduced size,

Lower coil resistance,

Heat sinking,

Heat fins and surface area increases,

Black body radiation coating,

Thermally conductive coil potting,  
Air convection -eddy cooling / integrated micro pumping structures,  
Pulse-Width Modulation / Duty cycle,  
Current control on pulsing.

Braking efficiency and friction can be to be improved.

Solved by:

Improved materials selection  
Non isotropic lubricants.  
Surface finish enhancement.  
New ceramic composites.  
Higher precision

Brake wear.

To be solved by:

non square wave signals,  
improved materials selection,  
better adjustment methods,

Fabrication costs.

To be improved by:

refined design,  
custom tooling,  
volume production and methods,  
reduced parts count

Size.

To be improved by:

refined design,  
refined fabrication fixtures and method,  
improve tolerances on key elements,  
possible inertial drive, single brake methods.

Terfenol-D rod breakage.

To be solved by:

Calibrated preloading measurements,  
Better machining of rod ends,  
Better parallelism on tolerances,  
Torsion de coupling.

Coil insulation wear

Solved by combination of:

Terfenol friction isolation, Teflon,  
Mechanical isolation gap,  
Thermally conductive lubricants,  
Potting coil to motive cell housing,

End cap centering.

Motor control

Improves with:

- Higher frequency motor,
- Higher PWM bandwidth,
- Possible Current control,

Exoskeleton issues.

Enhanced by:

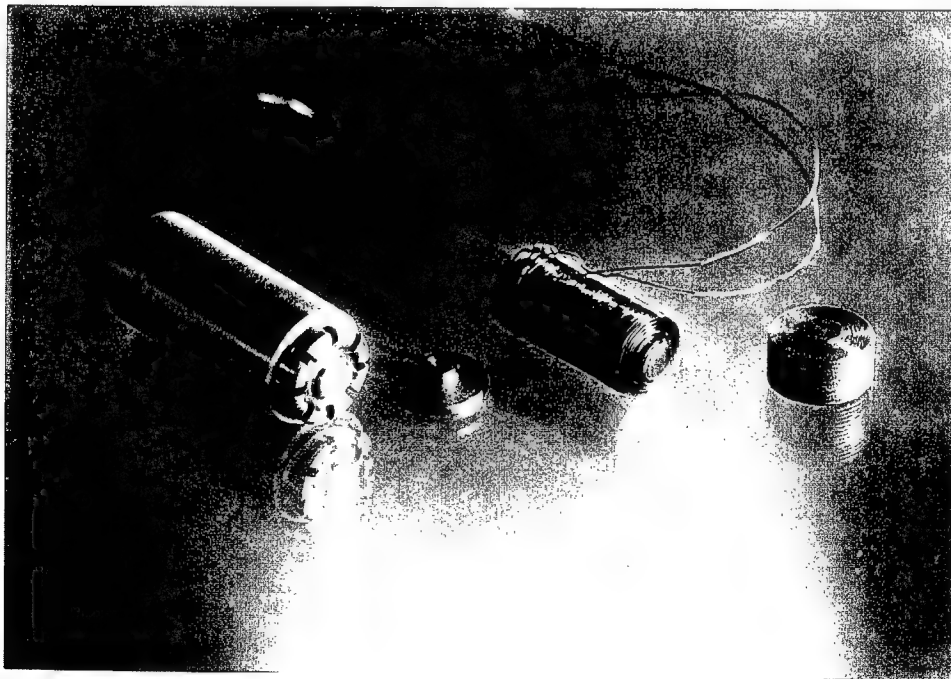
- More elegant (superior) motor/joint integration,
- Smaller motor,
- Stiffer drive shaft,
- Possible motor- virtual joint integration,
- Better manufacturing tolerances,
- More rigid materials;
  - Use of engineering plastics such as,  
graphite filled and LC polymers.
- More elegant implementation,
- Reduced friction in Joints;
  - Bearings, lubricants, materials
- Smaller load cells on finger pads,
- Smaller angle sensor implementation,
- Minimize cabling,
- Reduce cable stiffness;
  - Higher grade cable materials for flexibility
- Simpler adjustability methods.
- Reduced parts count.

The list is not comprehensive but should give a good indication of future development and improvements that can be effected with continued engineering. It is reasonable to expect improve performance as the technology matures.

At this position in the report we include photographs which have been referenced above.



Photograph 1. Three early Motive Cell prototype configurations.

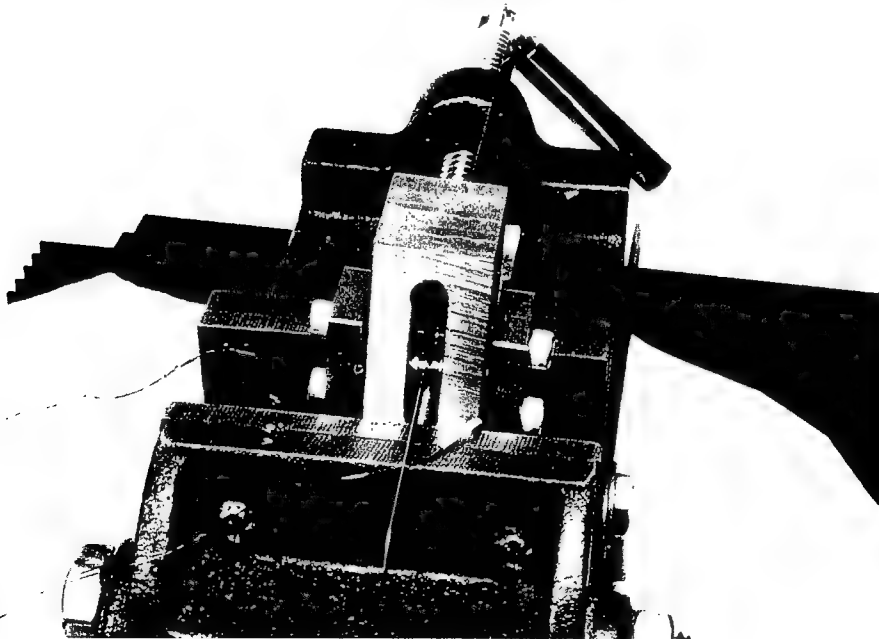


Photograph 2. Motive Cell before assembly

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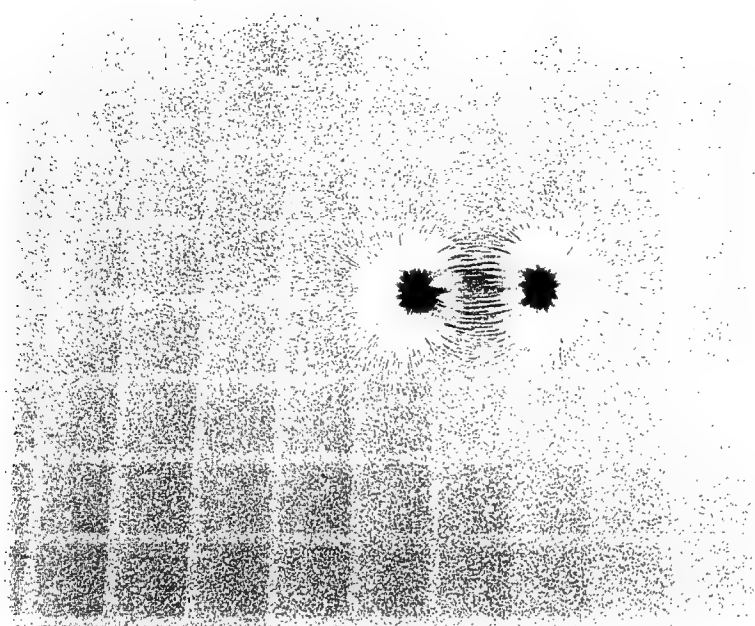


Photograph 3. Motive Cell for frequency response testing.

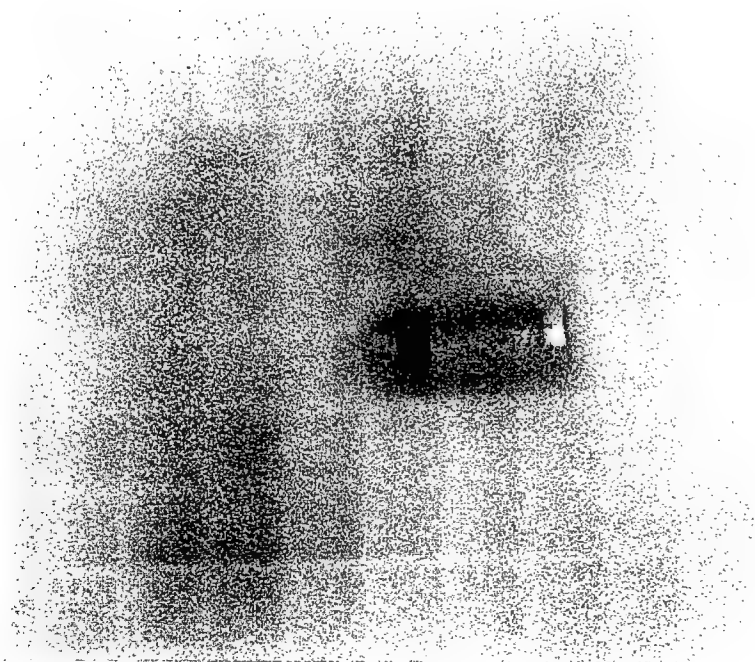


Photograph 4. Motive Cells as brakes, testing wear and forces on shaft materials.

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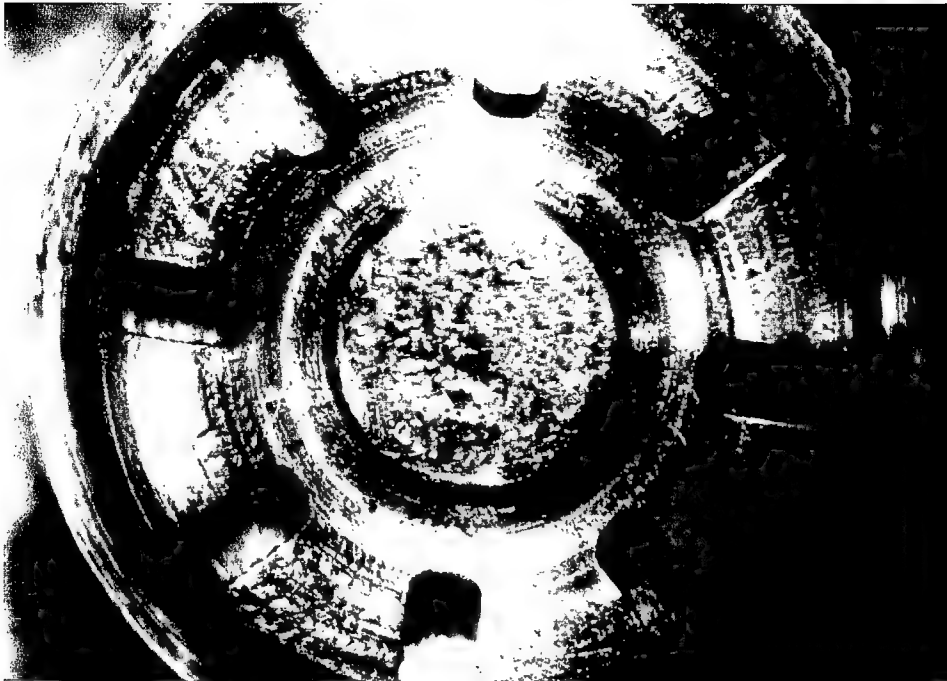
Photograph 5. Magnetic circuit testing, coil and Terfenol-D.



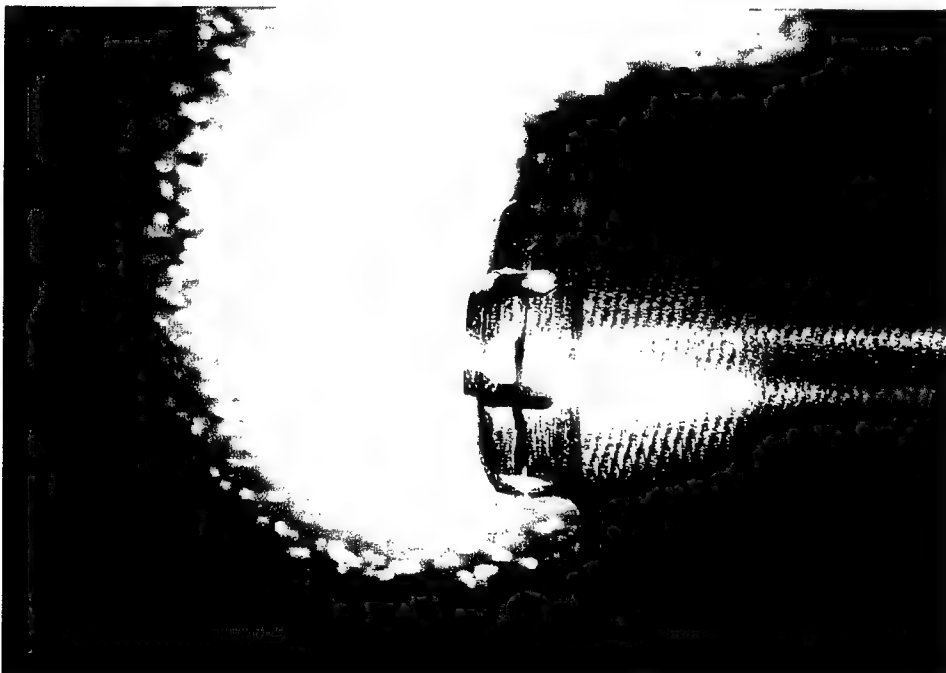
Photograph 6. Magnetic circuit testing, Motive Cell with flux return element.



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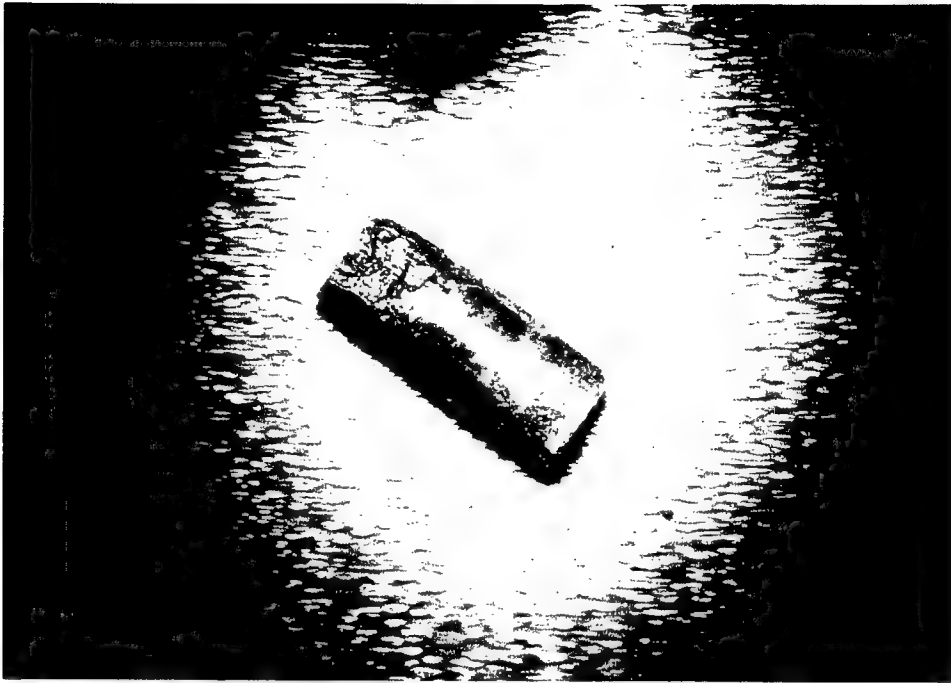


Photograph 7. Failure study, wear on Motive Cell brake pad.

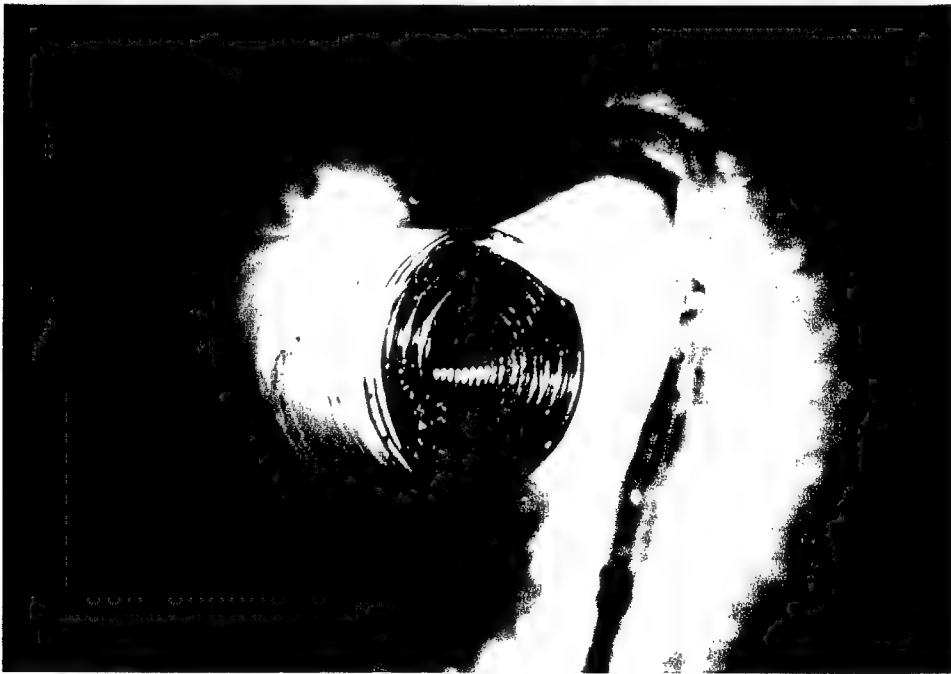


Photograph 8. Failure study on flexure failure. Failure due to poor machining tolerances.

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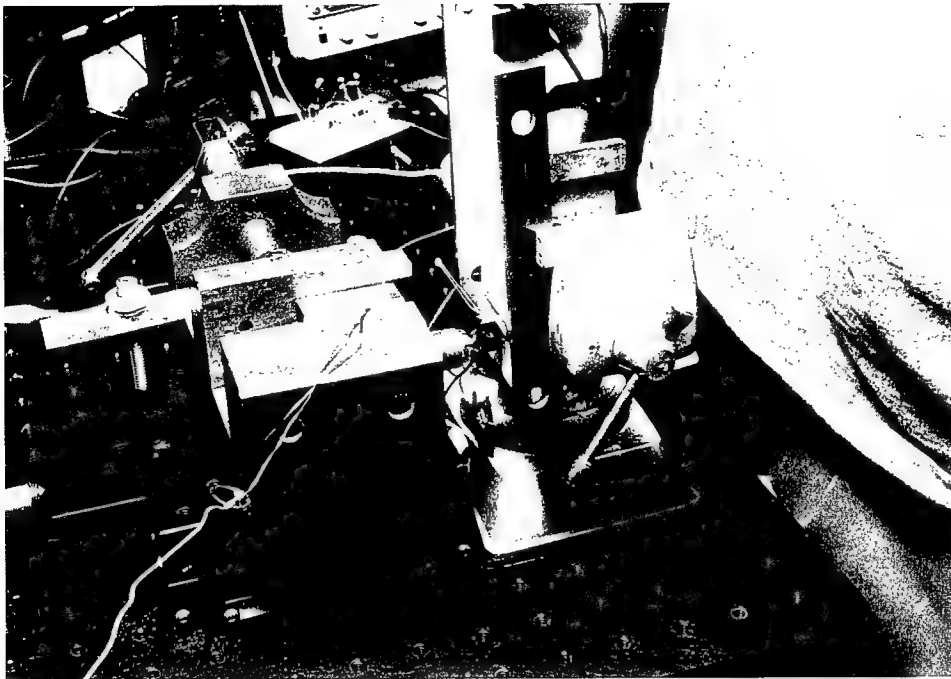


Photograph 9. Terfenol-D rod failure due to over tightening Motive Cell.

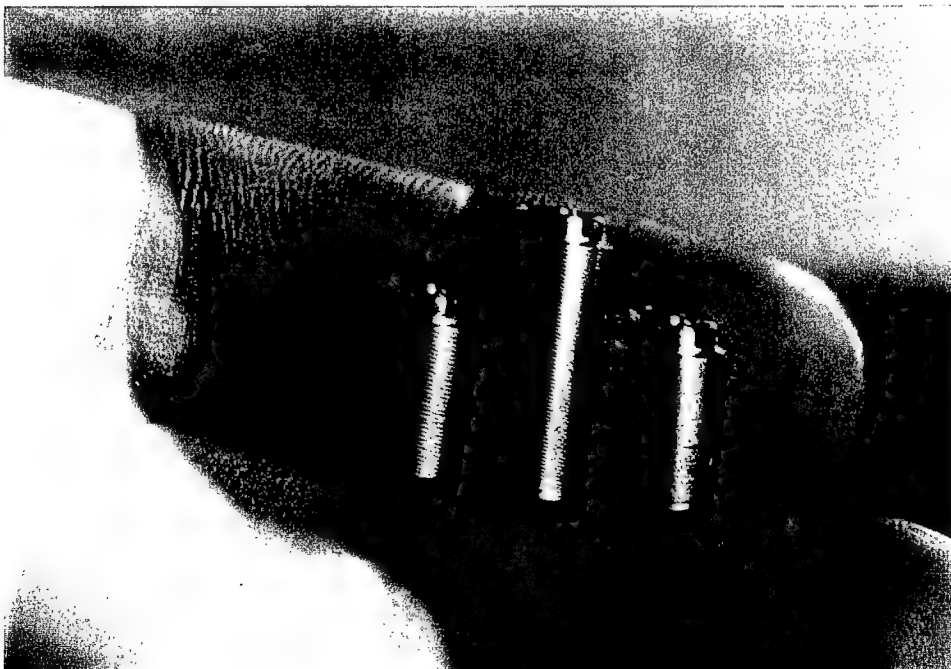


Photograph 10. Motive Cell failure due to insulation wear on driving coil.

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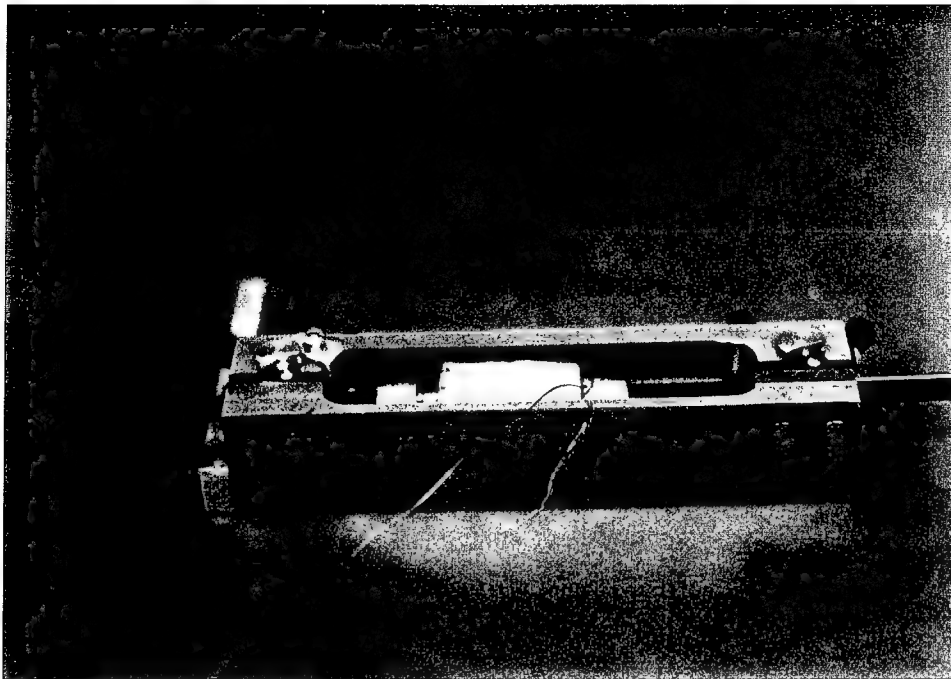


Photograph 11. Motive Cell frequency response testing setup.

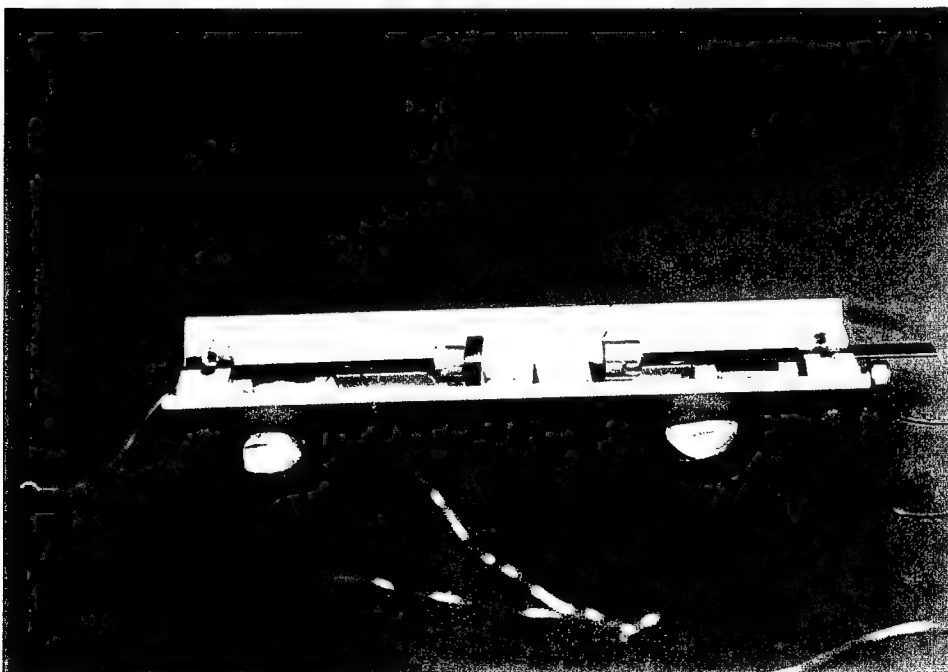


Photograph 12. Selected Motive Cell sizes to be integrated into final motor.

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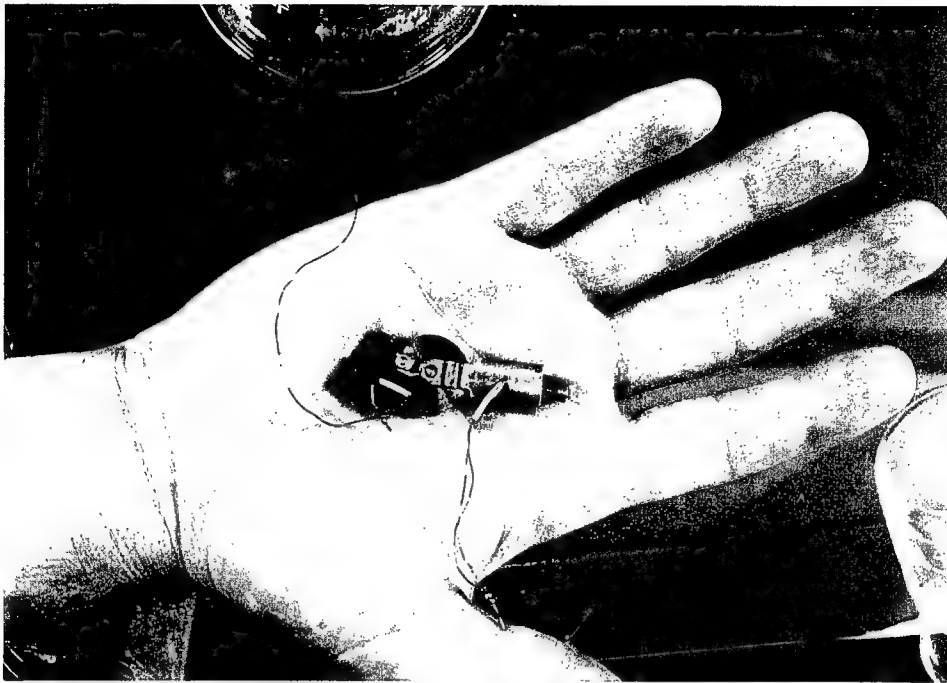
Photograph 13. Inchworm concept, brake test prototype.



Photograph 14. Inchworm concept test prototype.



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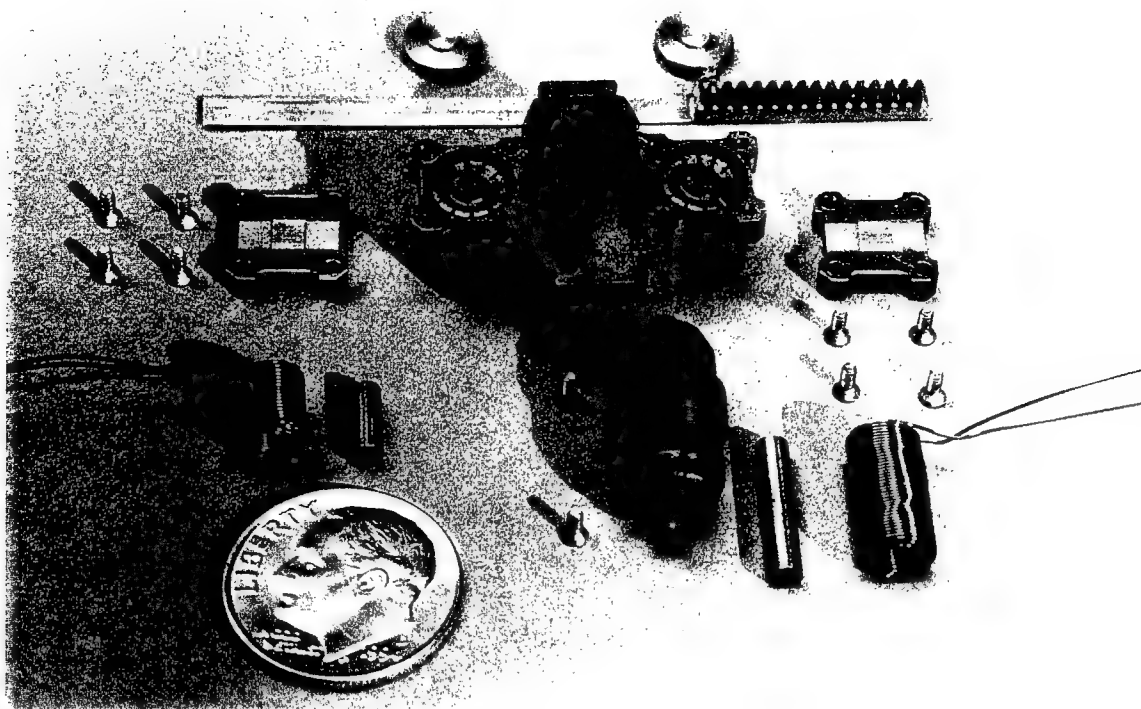


Photograph 15. Two element motor concept prototype.

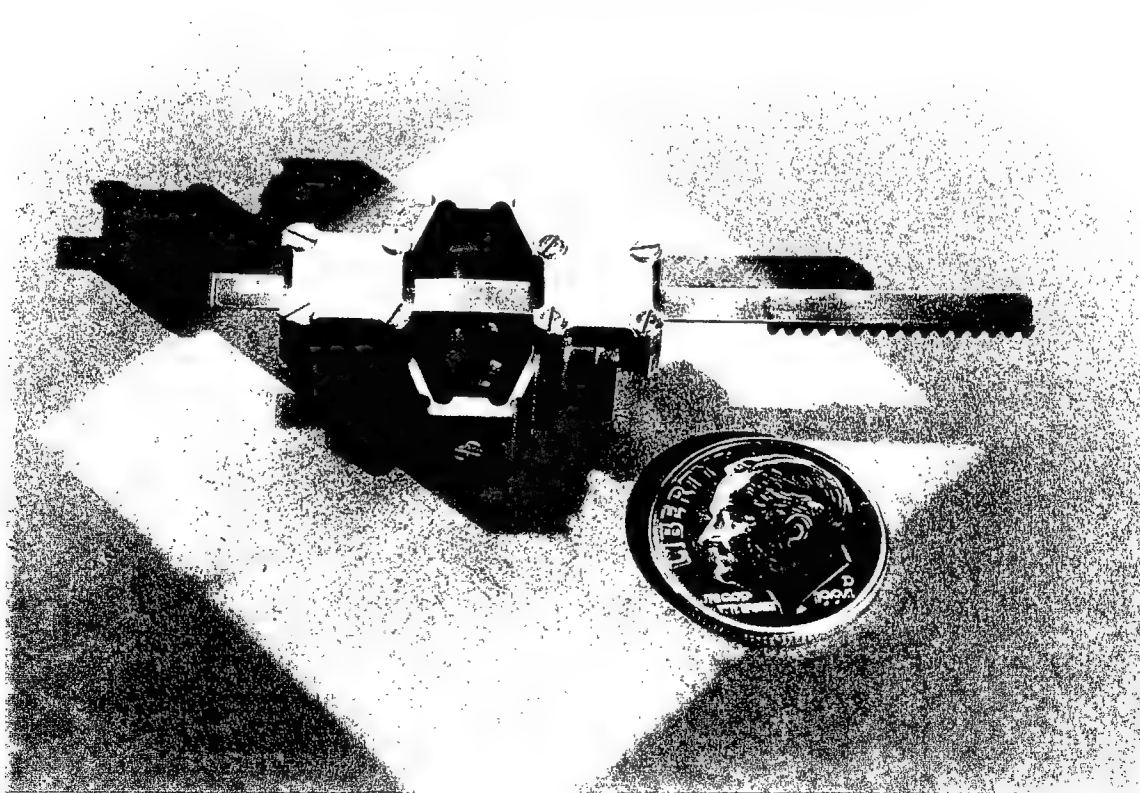


Photograph 16. First generation drive circuits.

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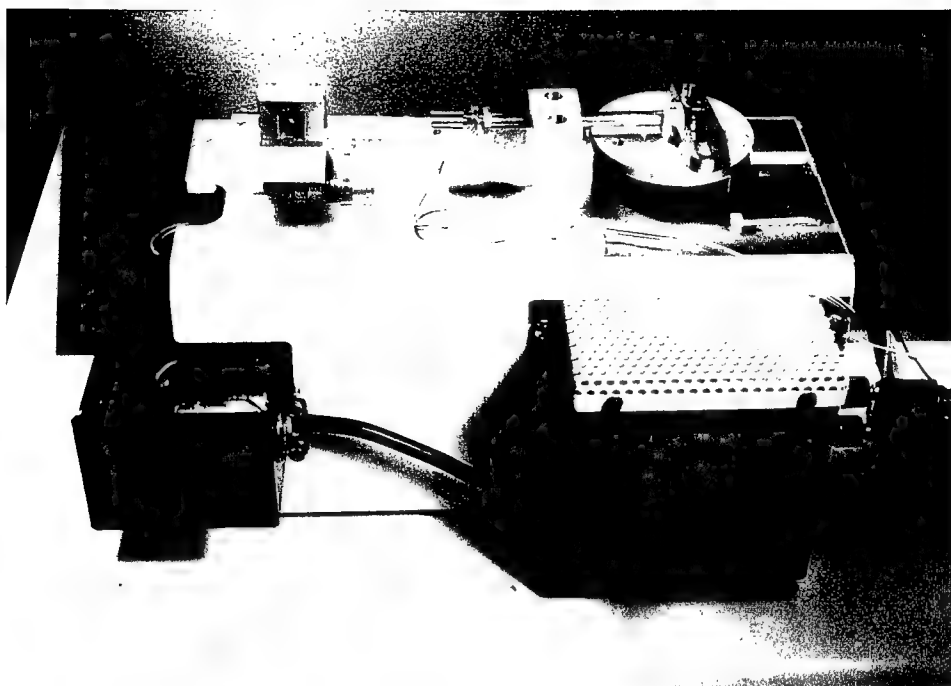


Photograph 17. Phase II inchworm motor before assembly.

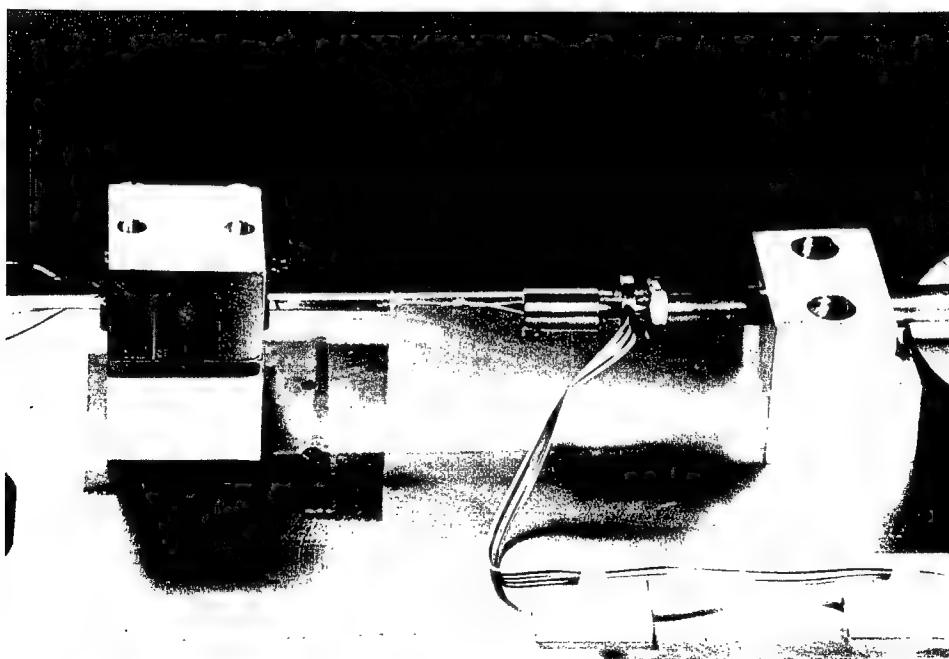


Photograph 18. Assembled Terfenol-D inchworm motor.

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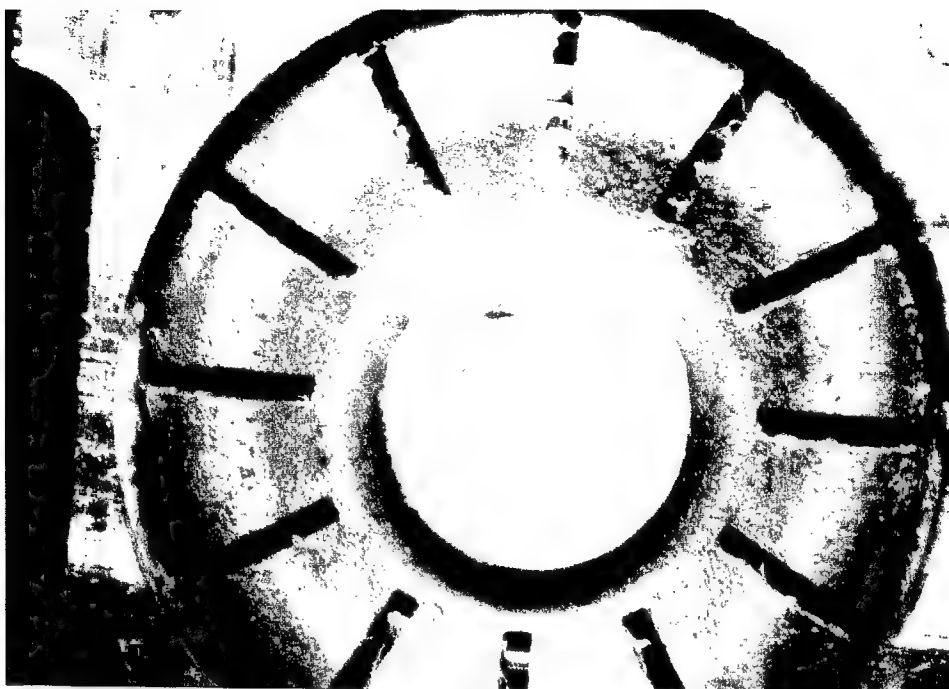


Photograph 19. Force testing apparatus.

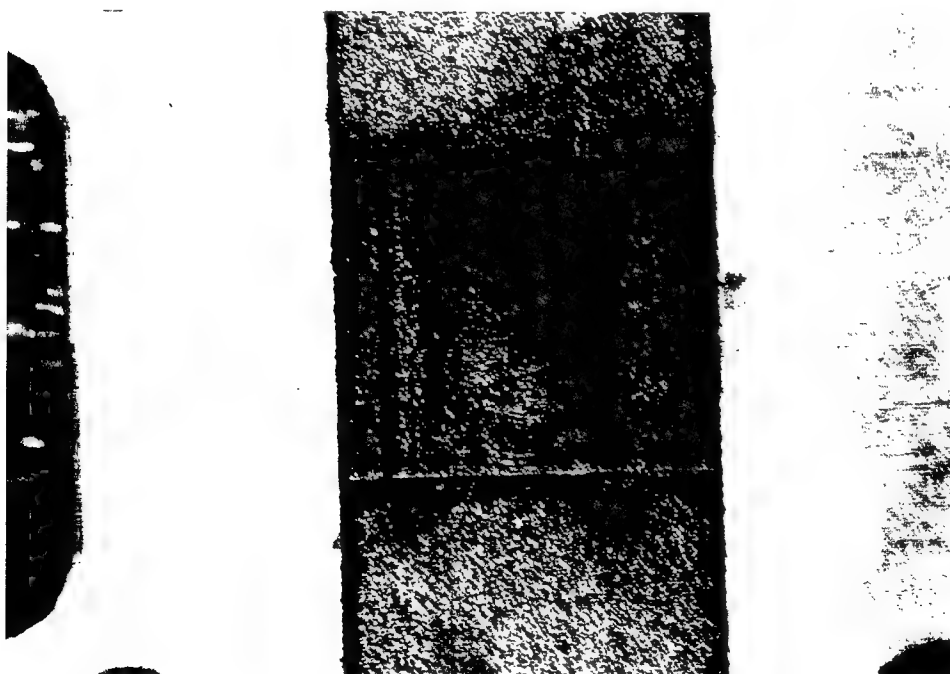


Photograph 20. Inchworm motor coupled to load cell on force, and position control.

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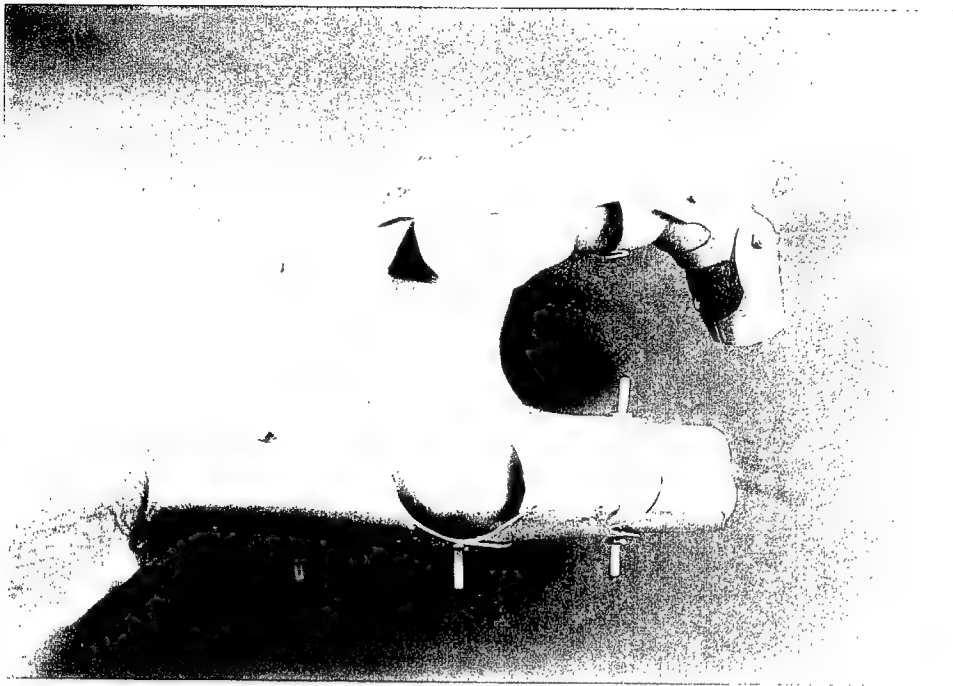
Photograph 21. Wear study on inchworm motor Motive Cell pad.



Photograph 22. Wear study on inchworm motor brake pad.



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Photograph 23. Exoskeleton joint study prototype.

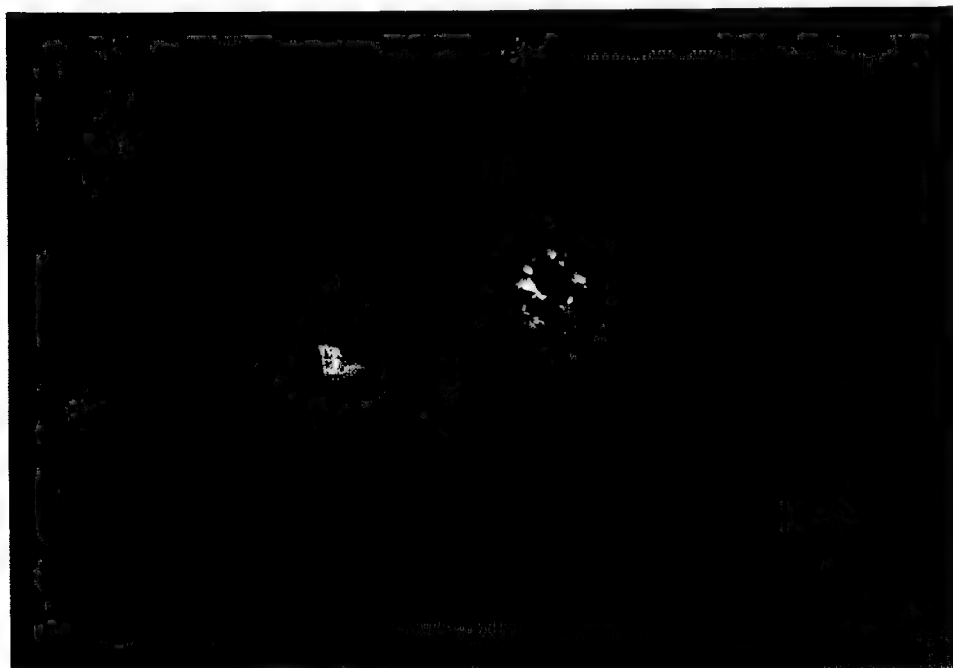


Photograph 24. Exoskeleton joint study prototype.

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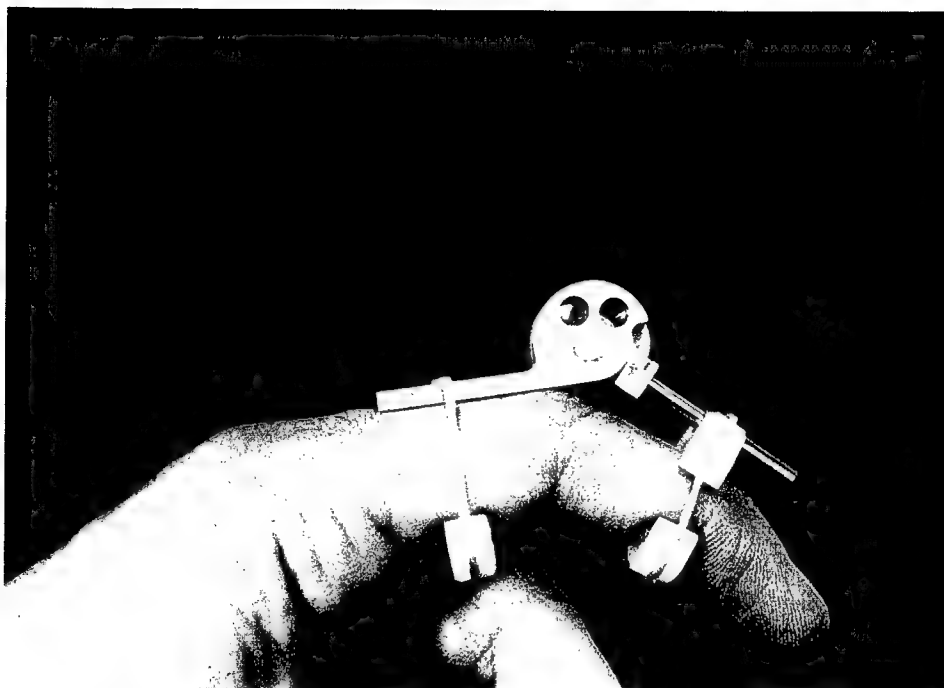


Photograph 25. Joint coupled exoskeleton prototype.

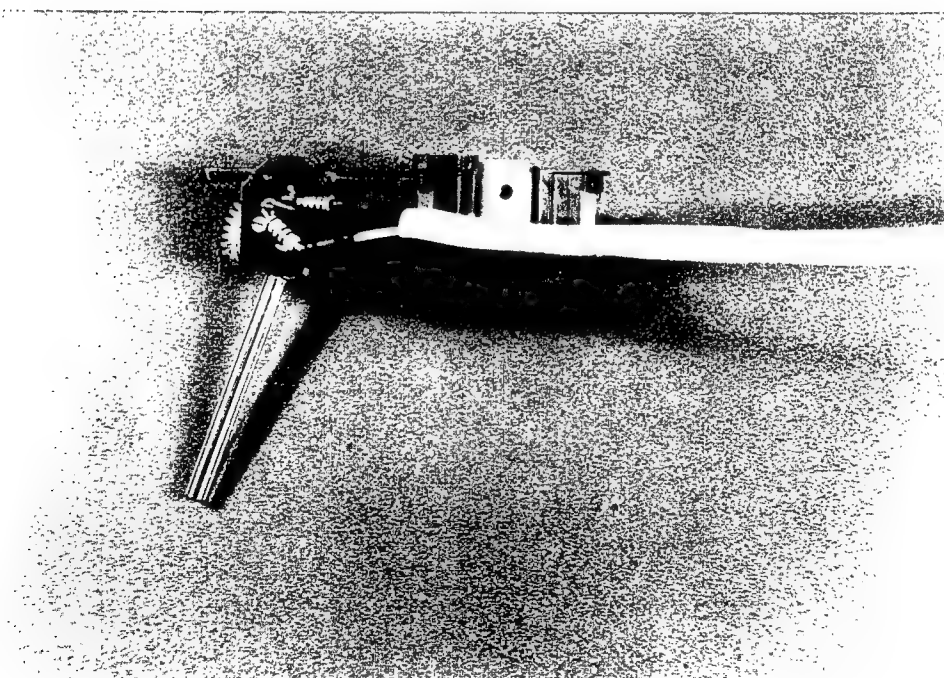


Photograph 26. Novel polarizer angle sensor.

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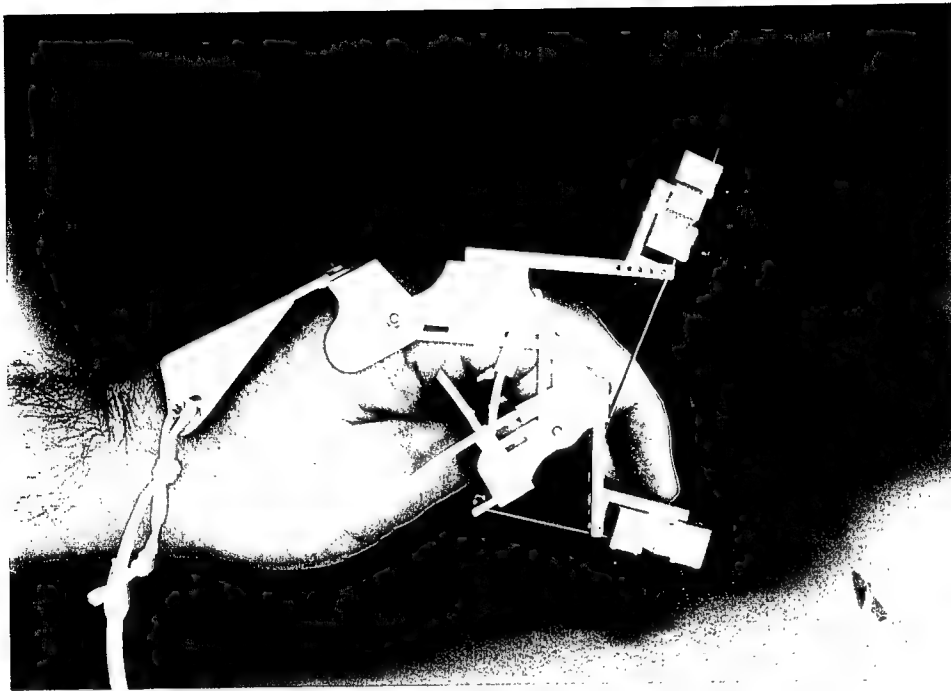


Photograph 27. Embedded angle sensor, joint study.

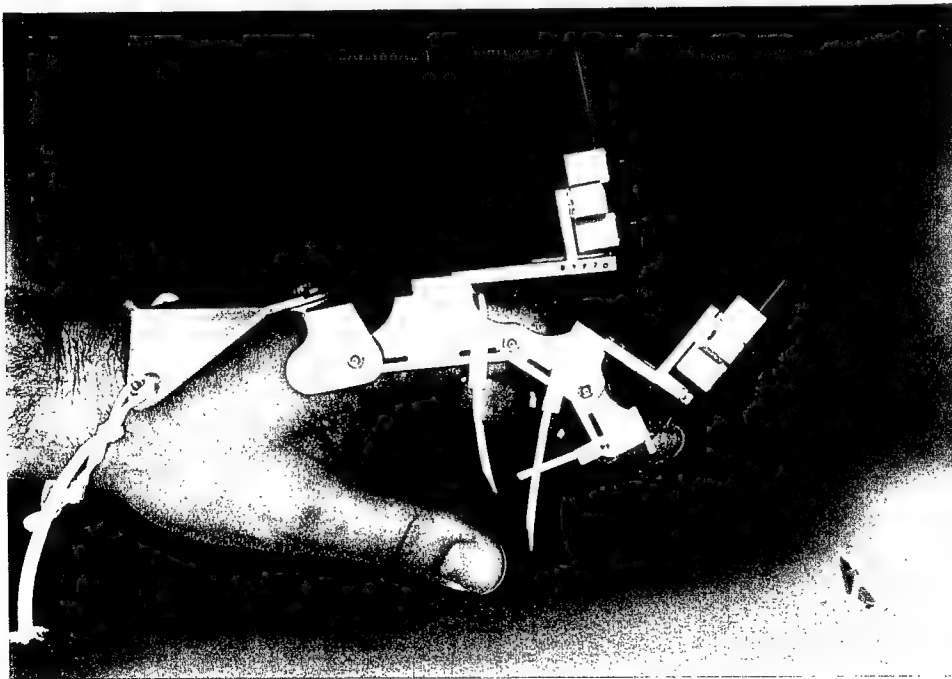


Photograph 28. Integrated rack and pinion joint, inchworm motor and angle sensor.

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Photograph 29. Pinned joint exoskeleton study with inchworm motor integration.



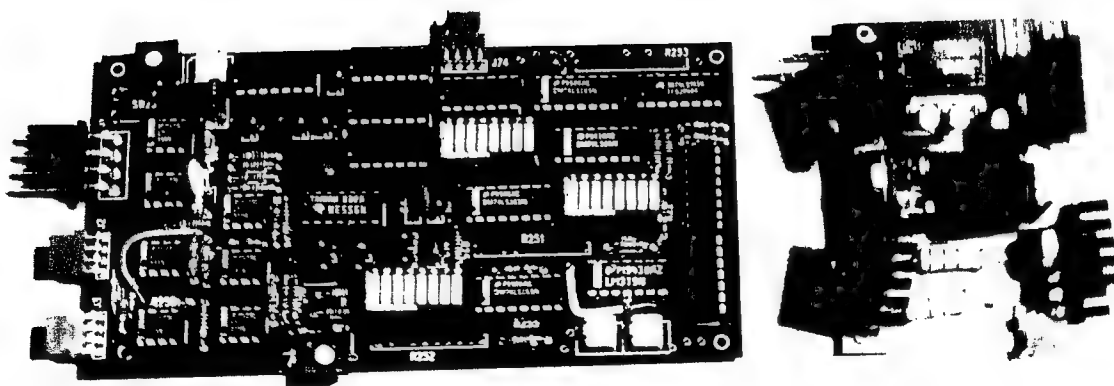
Photograph 30. Pinned joint exoskeleton study with inchworm motor integration.



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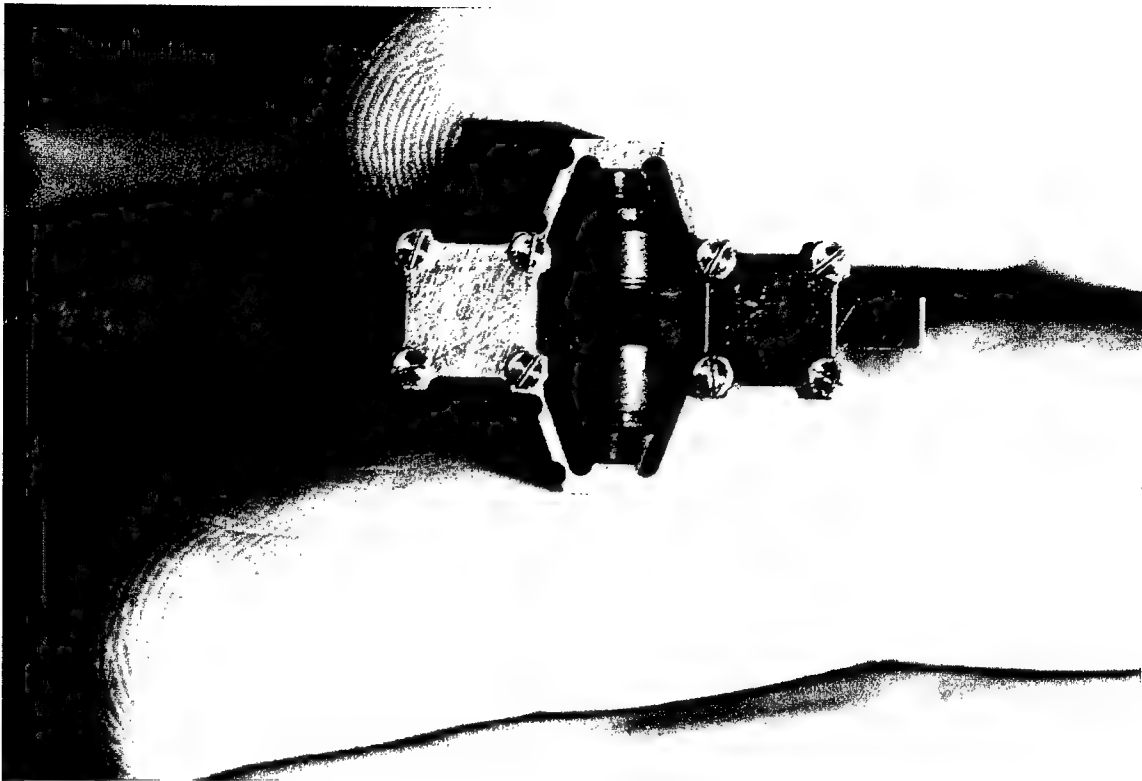


Photograph 31. Virtual Joint prototypes.

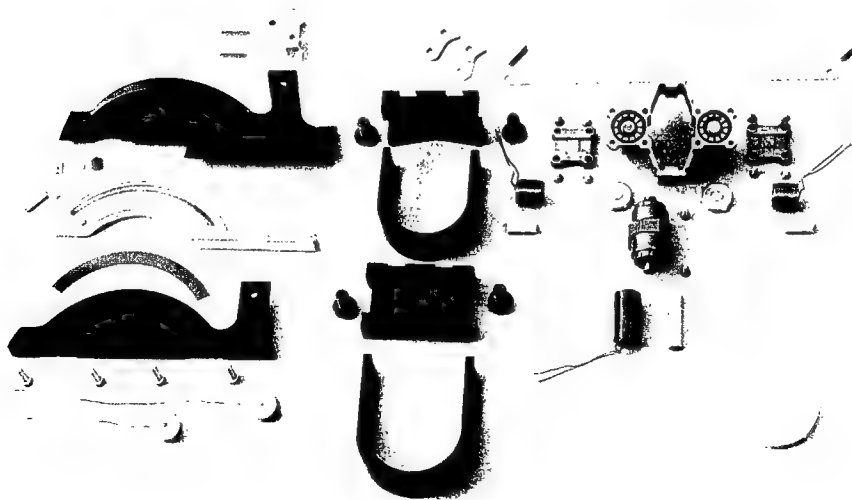


Photograph 32. Inchworm motor controller board, and motor switches.

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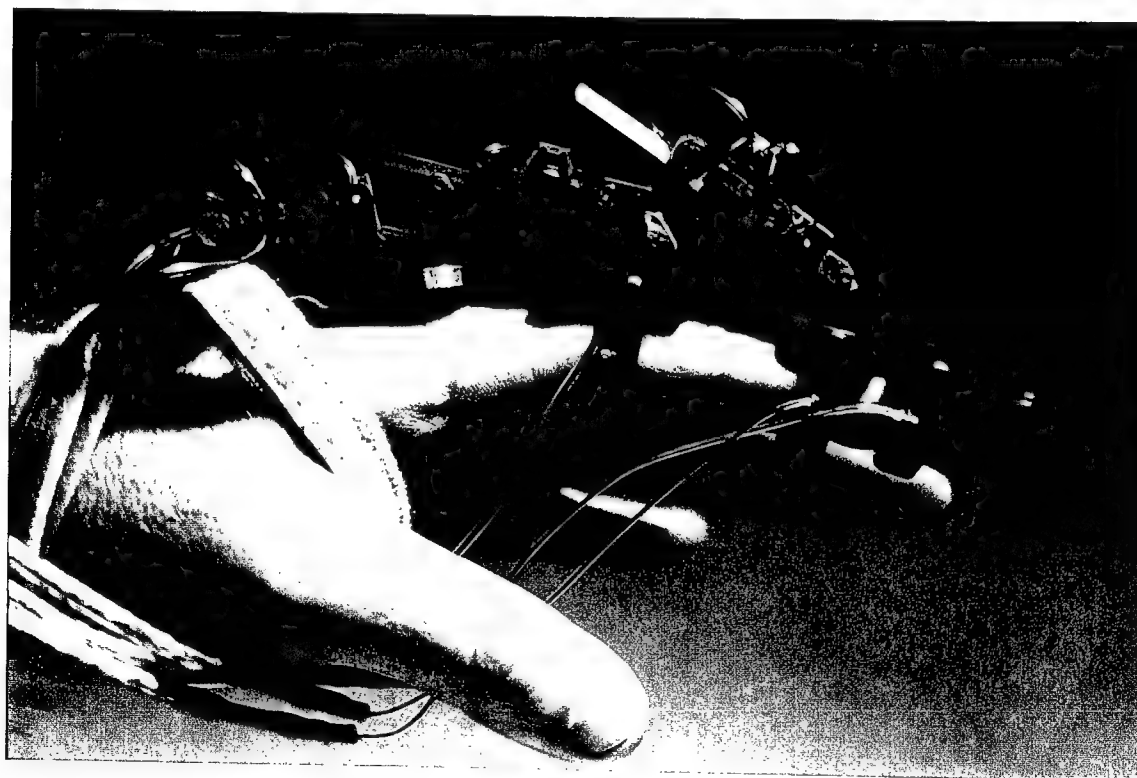
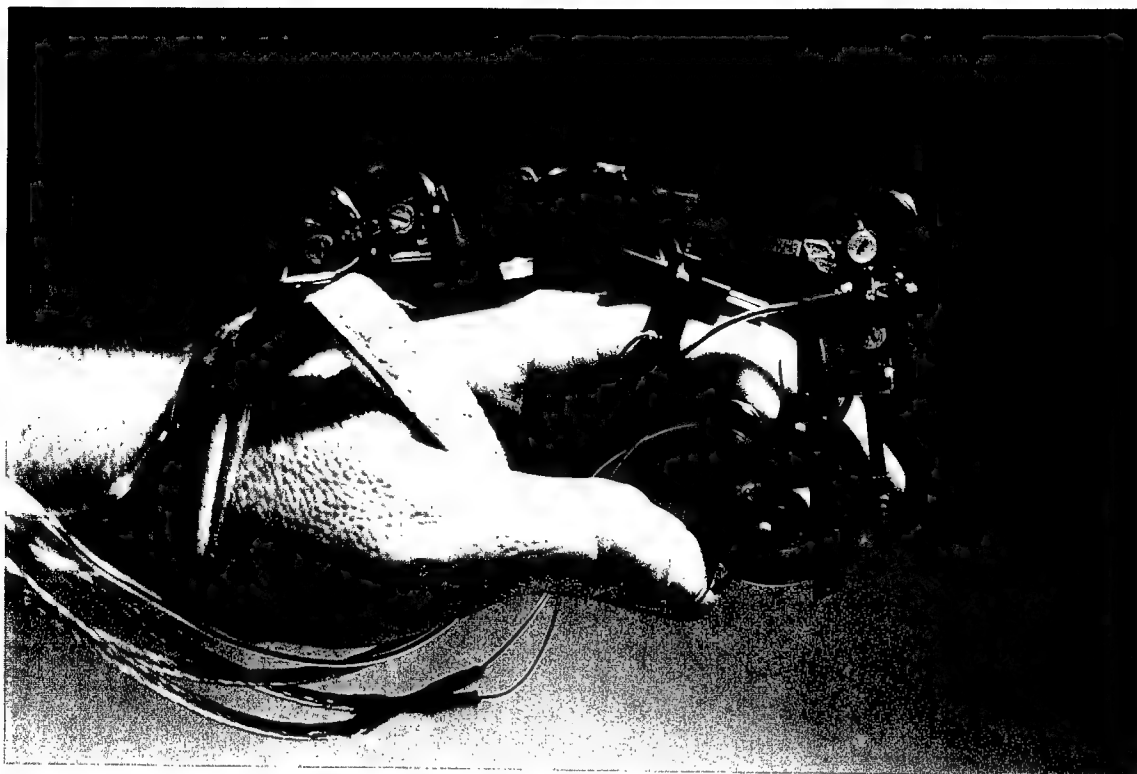


Photograph 33. Phase II final inchworm motor prototype.



Photograph 34. Exploded assembly photograph showing virtual joint and motor.

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Photograph 35. Final Phase II prototype, virtual joint exoskeleton. Three joint finger with imbedded polarizer angle sensors, Terfenol-D inchworm motors, and strain gage load cells.

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## ♦ Conclusions & Recommendation ♦

During the course of this SBIR Phase II project we have developed a novel magnetostrictive inchworm motor driven by Terfenol-D. It is appropriately scaled for dexterous exoskeletal feedback systems. The motor has demonstrated several new concepts and features previously untested using Terfenol-D. They include the following:

- Low voltage device.
- Small Size ~ 3 cc.
- Weight ~ 16 grams
- Forces compatible with human finger joints forces. ~ 10 N (per brake, i.e. 20 N max.)
- Velocity compatible with human finger joint velocities. 14.5 cm/sec =
- Rapid response time. 0.2 msec compatible with human tactile senses.
- High Frequency Driving (brakes to 10 kHz, motor to 5 kHz).
- Digital pulse control.
- Adjustability, i.e.. Locked or Freely backdrivable when power is off.
- Pulse Width Modulation Speed control.
- Pulse Width Modulation Force control.
- Current control of Force.
- Arbitrary force generation.
- Arbitrary force tracking.
- Constant force tracking on a moving object.
- Modular, mass production compatible.

In addition to the development of the new Terfenol-D motor prototypes we also developed several viable exoskeletal methods to integrate with the new motor. A new small geometry angle sensor was developed using polarizing elements. In this project the system of study included the human hand, force actuators, position sensors, force sensors, exoskeletal structure, electrical controllers, computer, software and ergonomic issues. Each of these elements also has subsystems such as coils, Terfenol-D, etc., which had to be developed in order to complete the overall goal of a demonstration exoskeletal joint with force feedback. The nature or broad scope of the project and its funding limits sculpted the final efforts. A broad understanding of the problem has been achieved and solutions to the problem have been identified. Patentable, state of the art systems have been designed, fabricated and tested. But much room for improvement can be identified. While the device developed for this project demonstrates size, force and velocity characteristics appropriate to the task at hand it can be significantly improved with some fairly simple design changes. Also solutions to the exoskeletal issues have been developed. Implementation of exoskeleton also needs improvement. The rudimentary software control and interface needs improvement. We have identified a number of problems and developed viable solutions but implementation will wait for future funding.

One of the most limiting parameters is the operational frequency. The motor, as built, is not particularly efficient above 5 KHz and driving the motor at 5 KHz creates a noise problem for this application. We have not addressed the noise problem at this point of the project since



the longer range goal was to develop a system that would operate above the audible range. Design for operation at higher frequencies has other advantages, such as increasing the energy density and improving heat transfer characteristics.

The exoskeletal virtual joints developed in this project also show significant promise. They provide a rigid, yet size adjustable platform. The system places the magnetostrictive actuators, virtual axes, and angle sensors out of the way of grasping motions, on the back of the fingers. The Terfenol-D motor/exoskeleton integration is in it's "Rube Goldberg" stage and needs future refinement and simplifying optimization. In continuing research the Terfenol-D motors could be imbedded into this virtual joint structure reducing bulk and streamlining the system. The motors have a high frequency response which could facilitate the development of an integrated tactile / force feedback system with a single digitally controled inchworm motor /actuator.

In summary, Terfenol-D based actuators show great promise as both a force actuators and a high fidelity integrated tactile/force actuators. The technology is still in its infancy when compared to DC motors, hydraulics, etc., but has inherent advantages such as energy density, and response time. The broader topic of anthropomorphic dexterous robotics and force feedback is also just getting a good start toward its desired long range objectives. The continued development of high energy density magnetostrictive devices could very well aid in overcoming exoskeletal related obstacles such as size, force, velocity, weight and fidelity.

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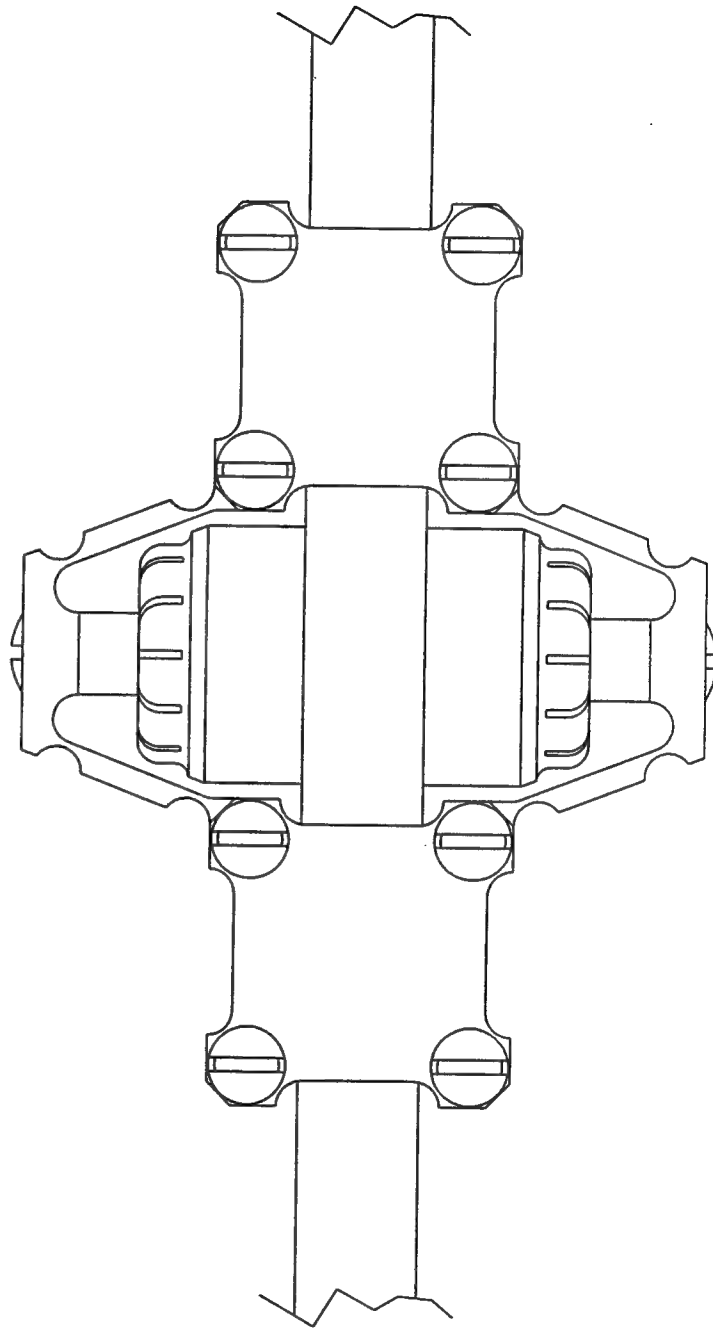
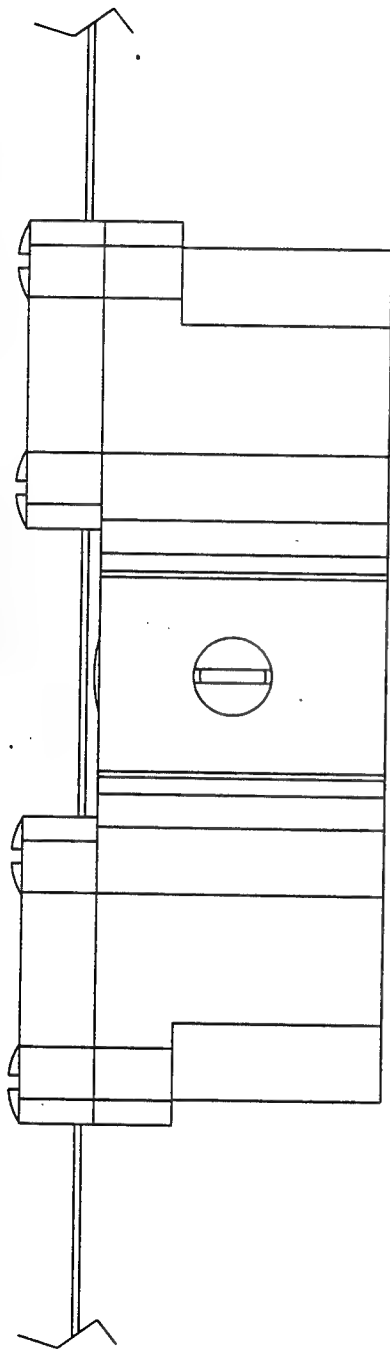
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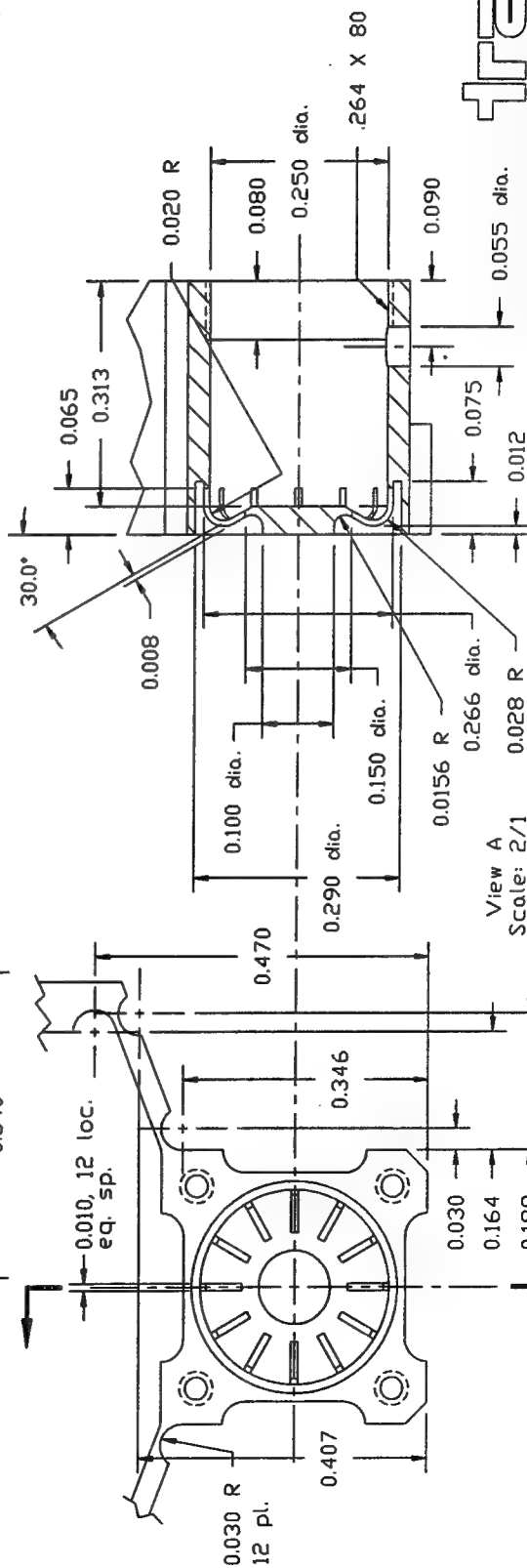
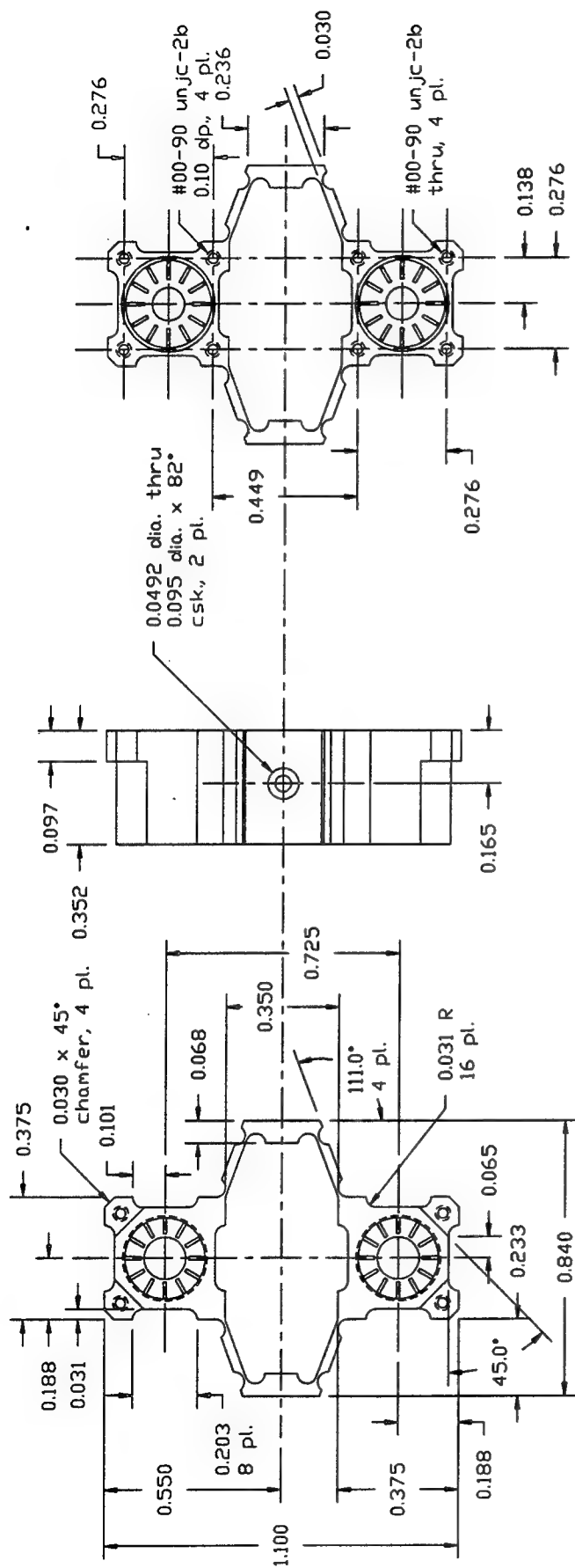
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## ♦ Appendix A ♦

### Mechanical Engineering Drawings



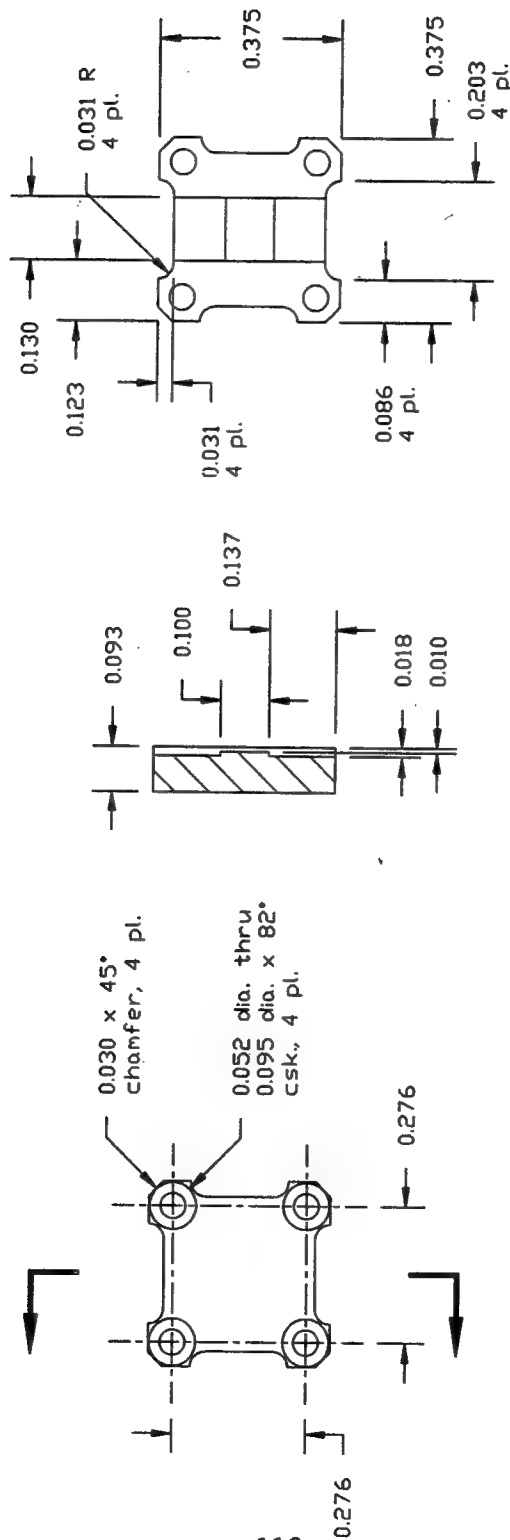


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APPROVAL	
No. BE100100	

TEL

Unless otherwise specified,  
Dimensions are in inches



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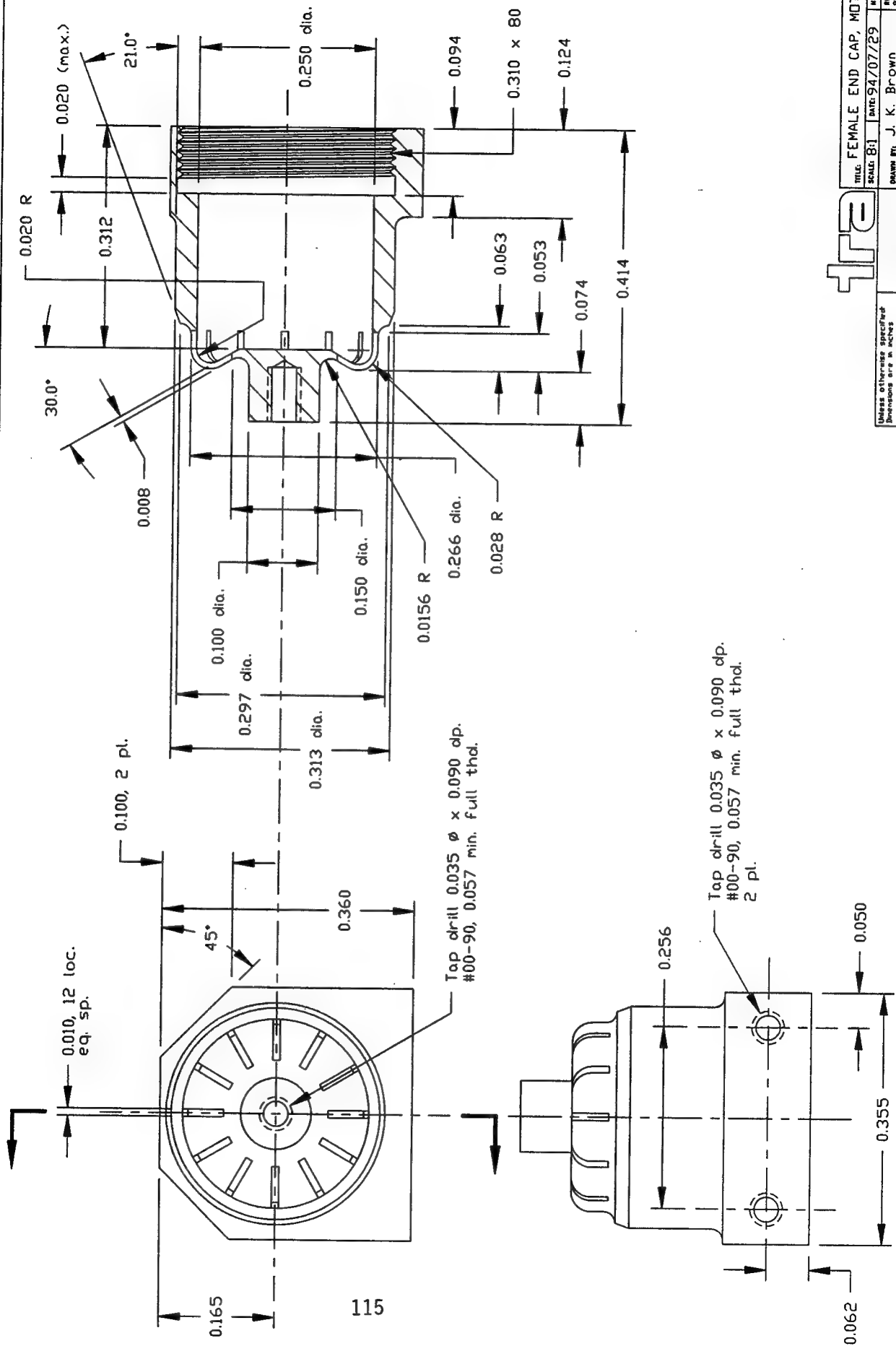
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APPROVAL	

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Rounded to 2 or 3X & 0.02



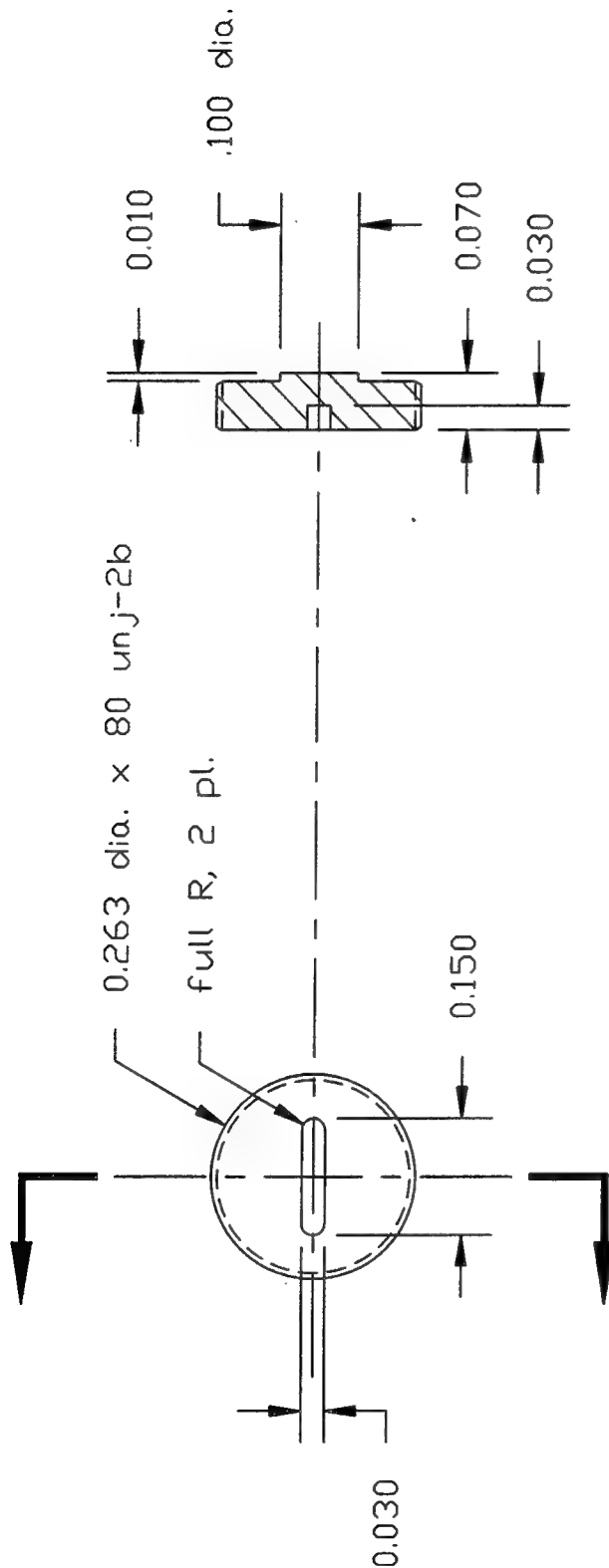


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FEMALE END CAP, MOTIVE CELL			
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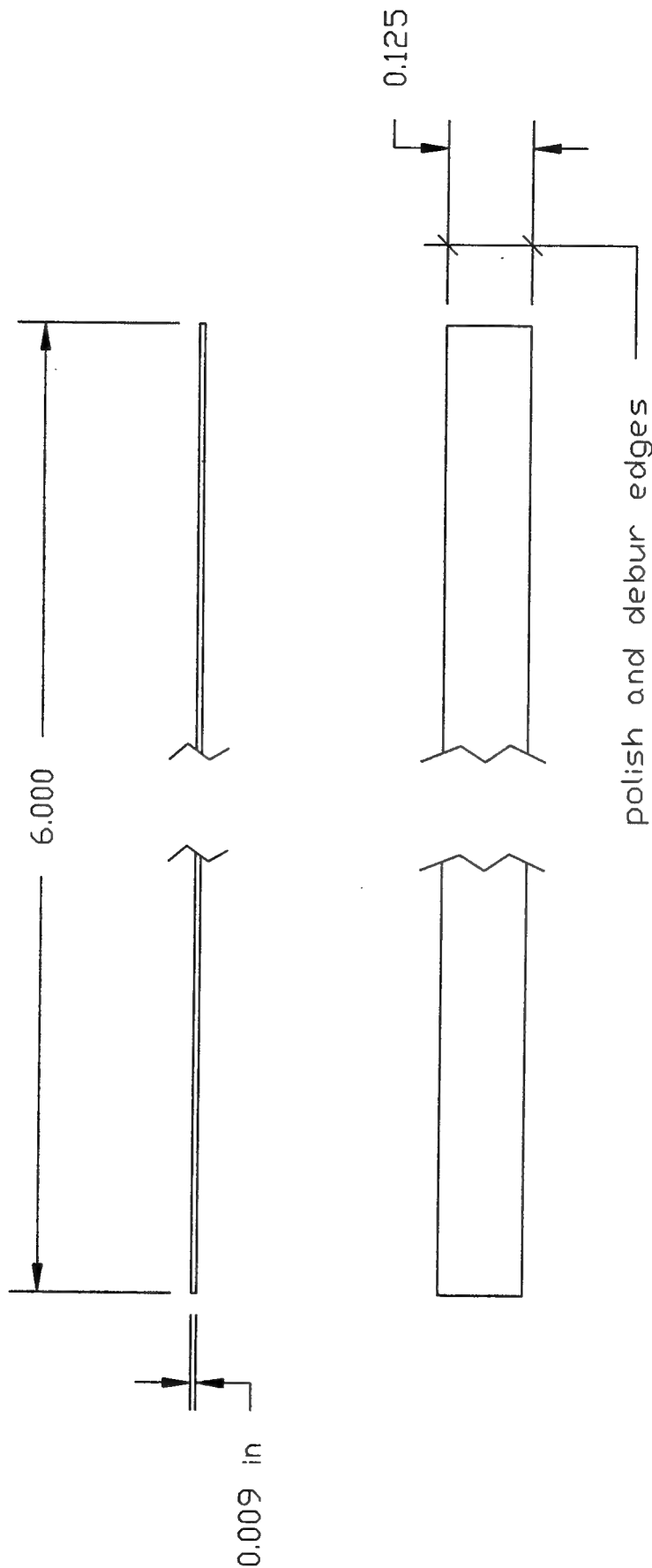


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 Decimals .XX ± .01, .XXX ± .002

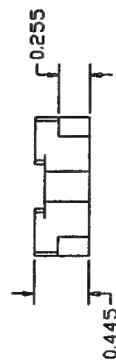
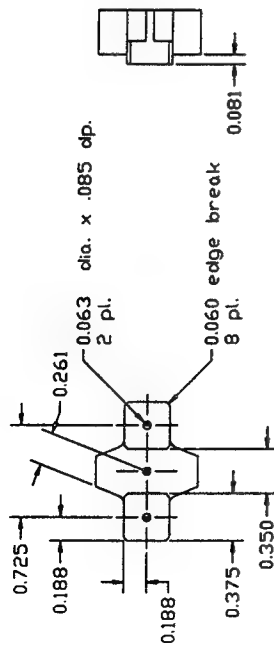
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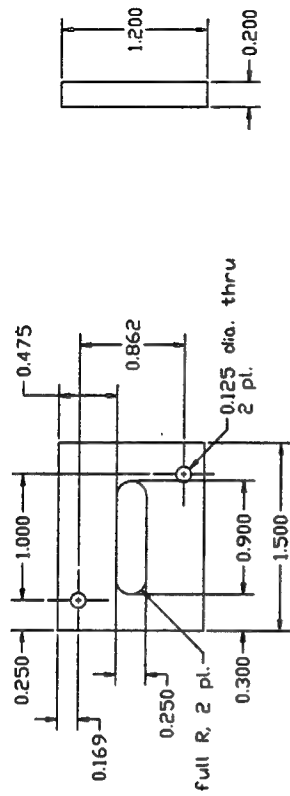
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tra

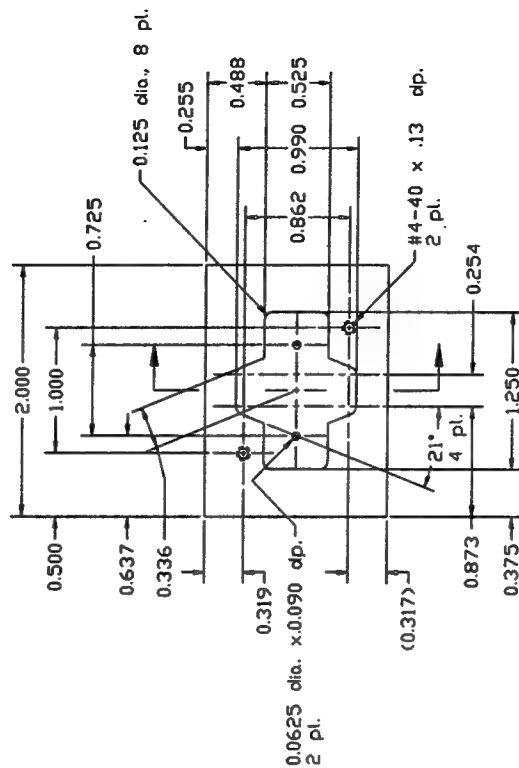
TITLE: RIBBON, LINEAR MOTOR		SCALE: 4:1	DATE: 94/09/30	No. BE100117
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON ANGLES ± 0° 30' DECIMALS .XX ± .01, .XXX ± .002		DRAWN BY: J. K. Brown		RELEASE DATE: 95/01/04
PROJECT: Actuators II		FILE NAME: motor5.dwg		APPROVAL:
Heat Treat: N/A				



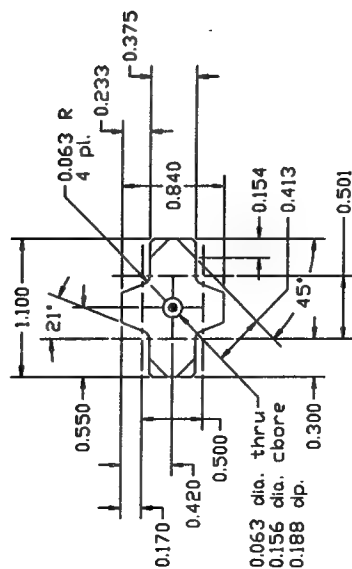
118



-7 Cover Plate



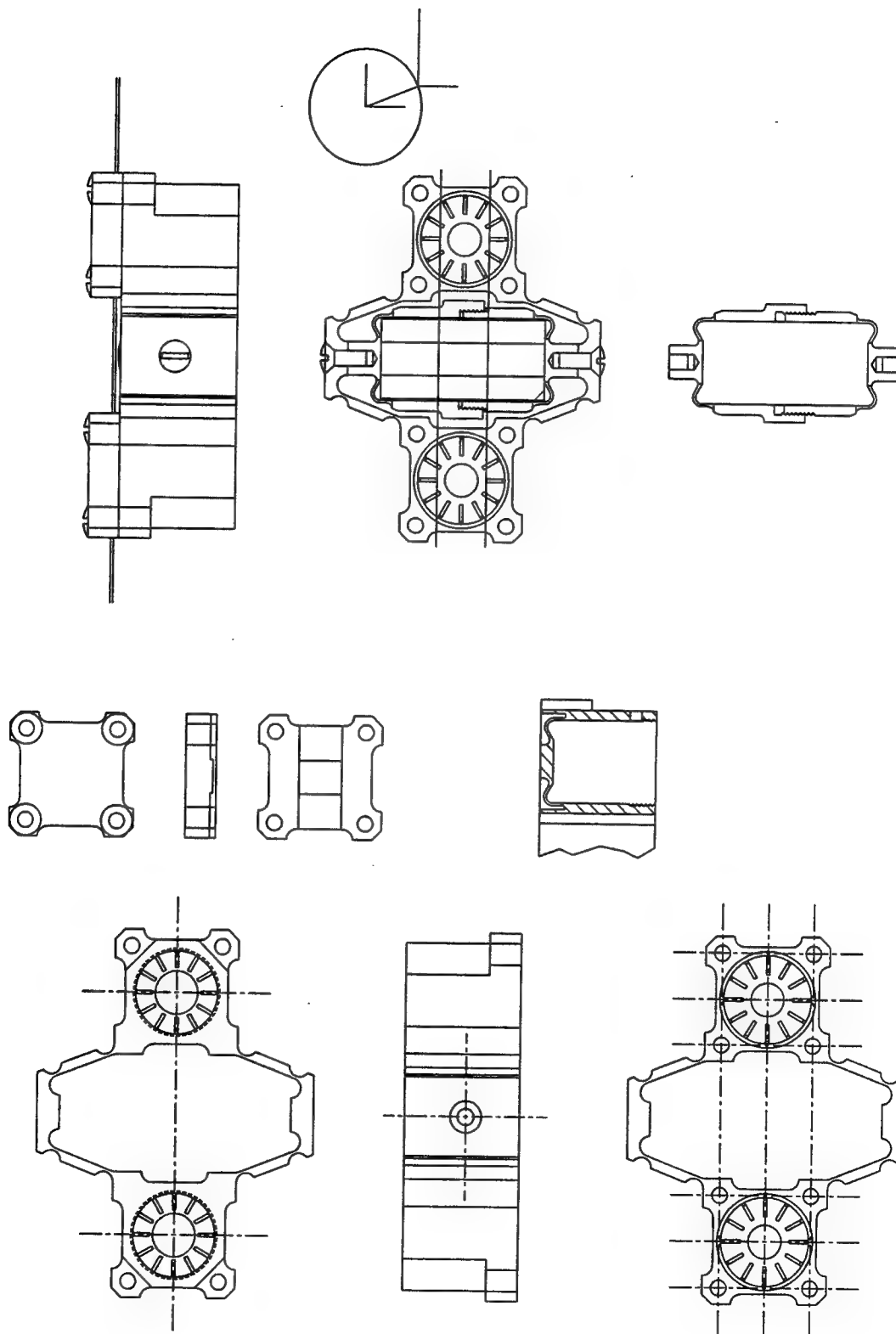
-5 Cavity



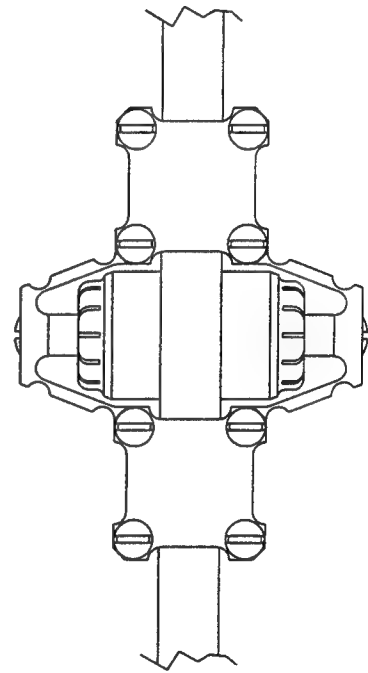
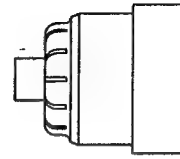
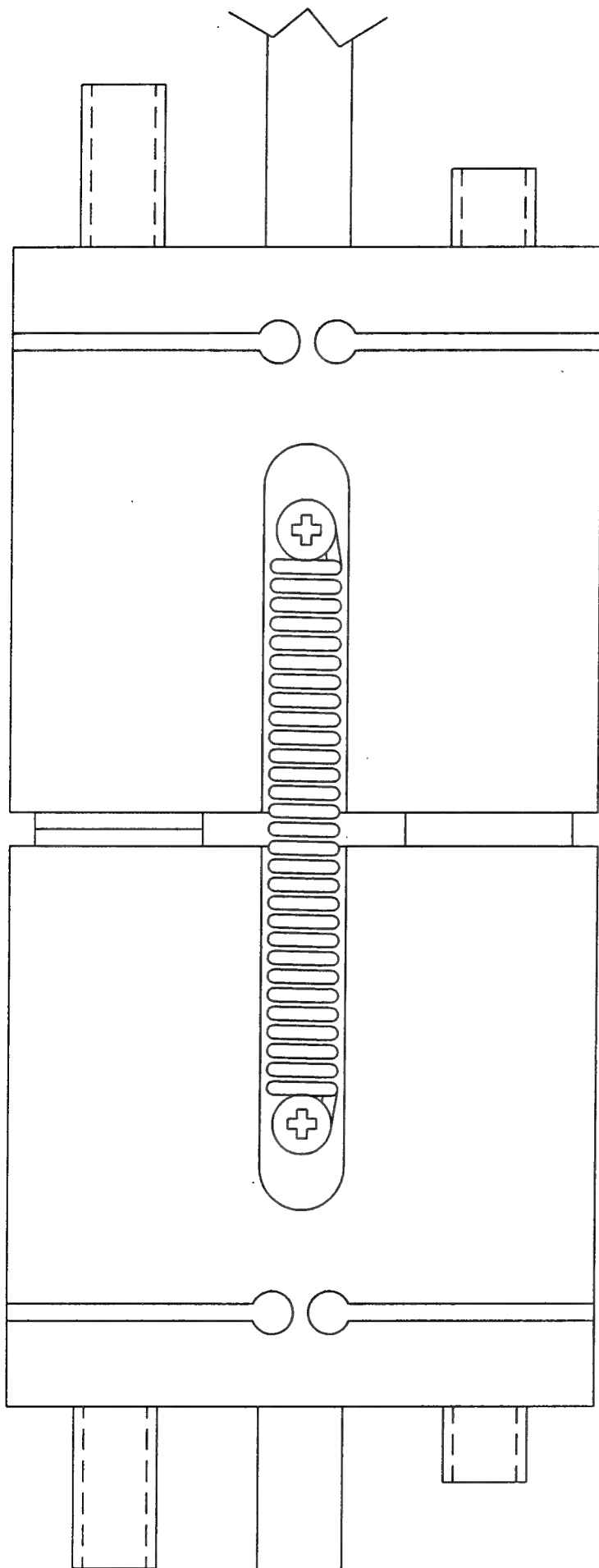
-3 Plug

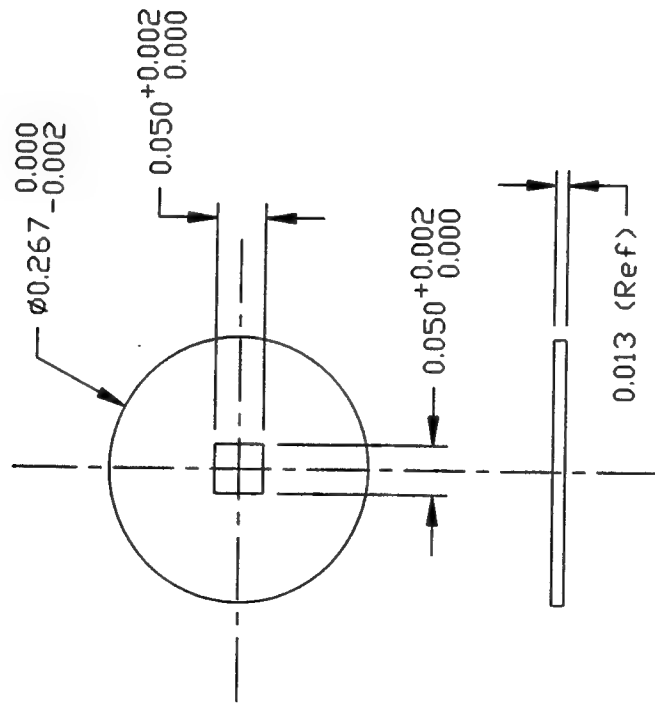
tra

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON ANGLES ± 0° 30'	DATE: 95/03/17	W: BE100123
DESIGN: J. K. Brown	PROJECT: Actuators II	RELEASE DATE: 95/03/27
REVISION: 1	TEST: 1	APPROVAL:
FILE NAME: motorfeet.dwg		

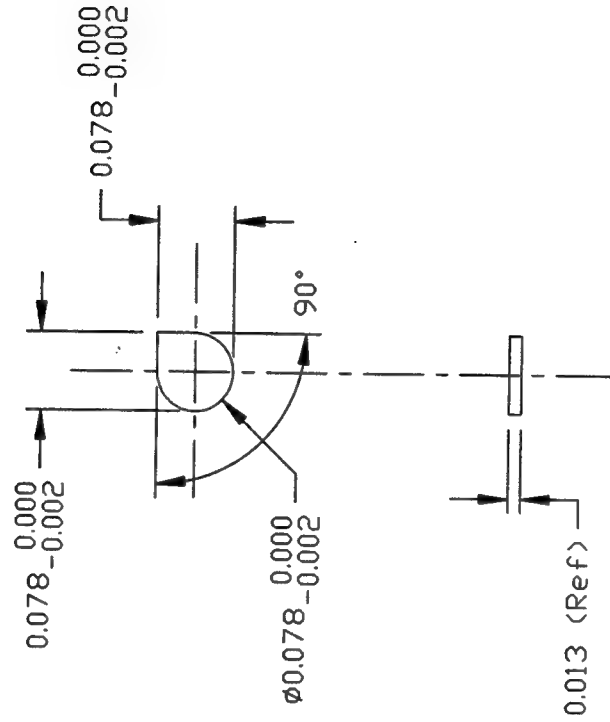


TITLE: XXX		SCALE: 4:1	DATE: XXX	NO. BE 00XXX
REV A		DRAWN BY: XXX	PROJECT: ACTUATOR II	REVISION: 3 MAR 94
REV A		NO. 11 XXX	FILE NAME: NOTICE.DWG	APPROVAL:
REV A		NO. 11 XXX	FILE NAME: NOTICE.DWG	APPROVAL:






-3 Detail

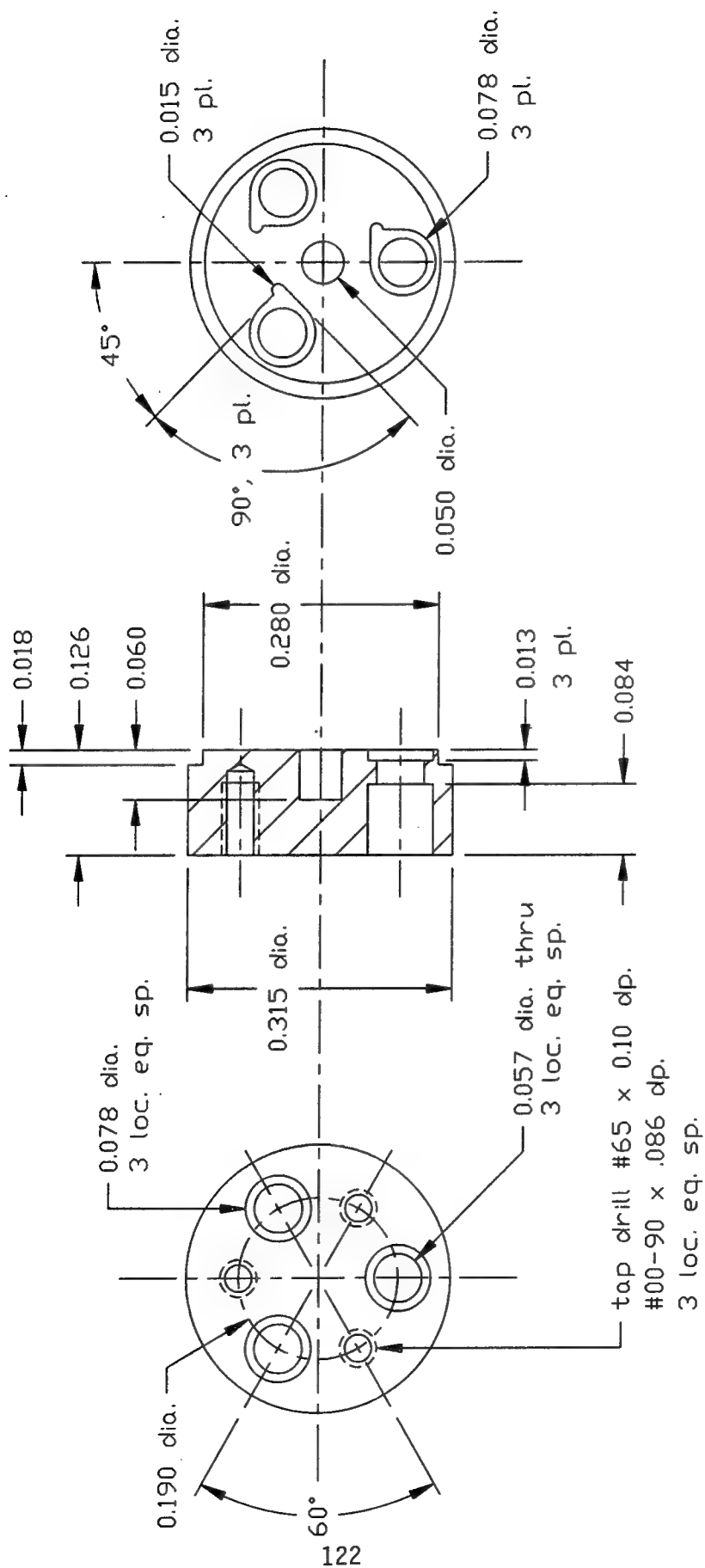


-5 Detail

1. Make from Glare Stop polarizing filter matl.  
Visual Pursuits, Inc.

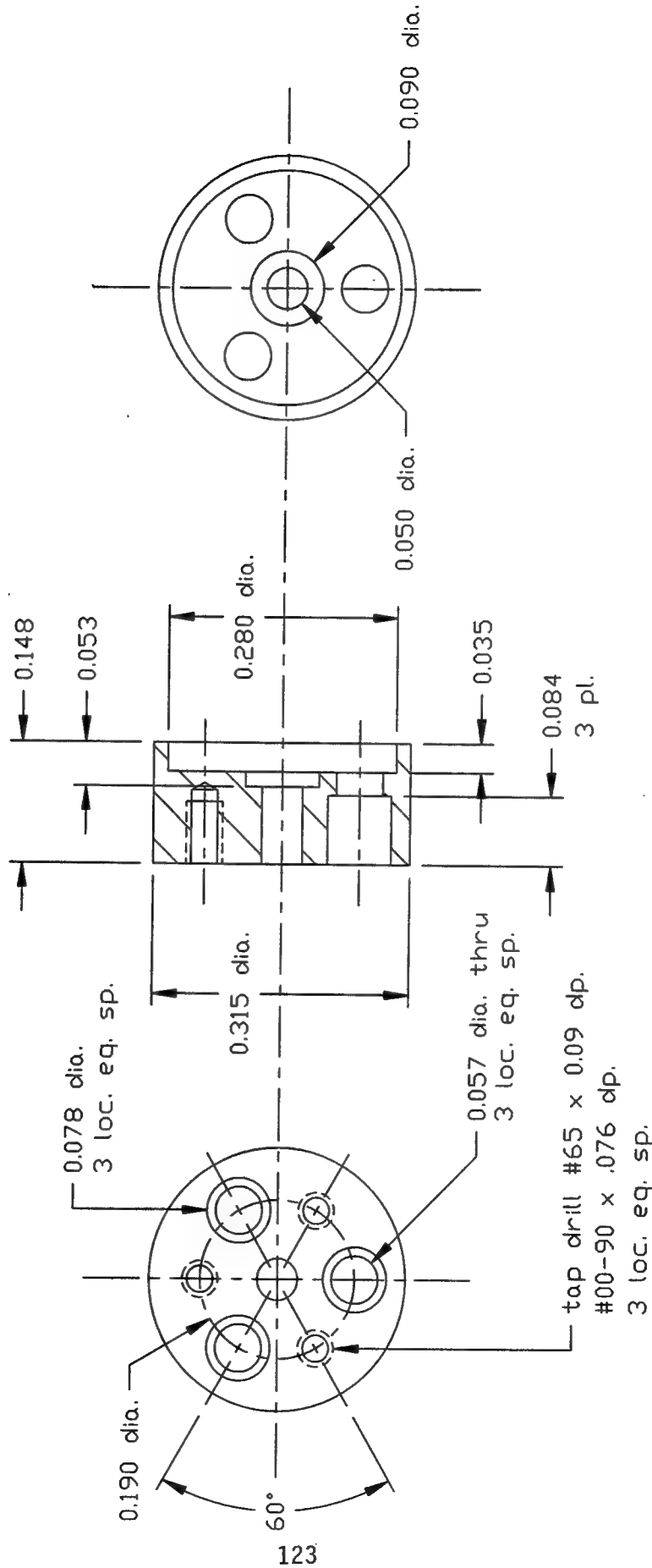
		POLARIZER ELEMENTS, R SENSOR SCALE: B1 DATE: 94/08/30 No. BE100104	
(Unless otherwise specified, dimensions are in inches)		DRAWN BY: J. K. Brown PROJECT: Assemblies II FILE NAME: P100104	
Tolerances on angles: 30° Decimals: XX ± .01, XXX ± .002		RELEASE DATE: 94/09/01 APPROVAL:	





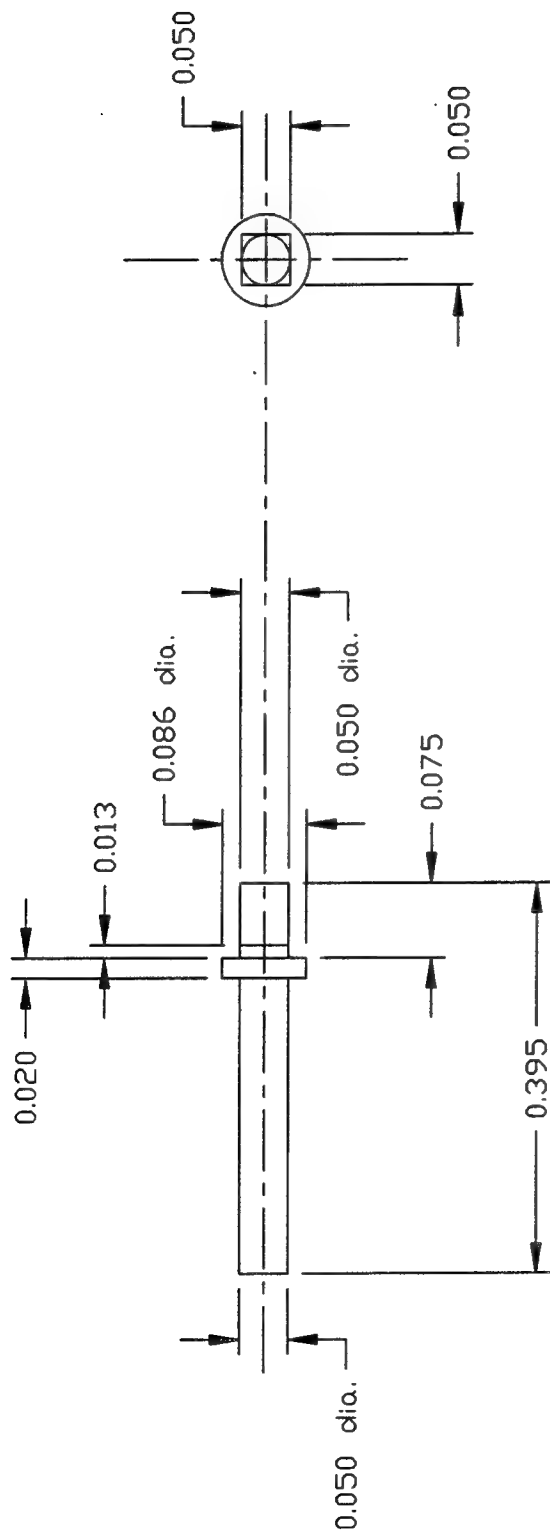
tra

TITLE: DIODE HOUSING, R SENSOR		DATE: 94/09/01	REV: BE100105
SCALE: 8:1	DATE: 94/09/01	DESIGN: J. K. Brown	DATE: 94/09/01
DRAWN BY: J. K. Brown		PROJECT: Actuators II	APPROVAL:
MATERIAL: Mill Brass		FILE NAME: resour2	
TOLERANCES: UNLESS OTHERWISE SPECIFIED			
DIMENSIONS ARE IN INCHES			
TOLERANCES ON ANGLES: ± 0° 30'			
DECIMALS: XX ± .01, XXX ± .002			
HEAT TREAT: N/A			



tra

TITLE: DETECTOR HOUSING, R SENSOR		DATE: 94/09/02	REV: BE100106
SCALE: 8:1		DATE: 94/09/02	REV: BE100106
DRAWN BY: J. K. Brown		DATE: 94/09/02	REV: BE100106
PROJECT: ACTUATORS II		DATE: 94/09/02	REV: BE100106
FILE NAME: reseed3		DATE: 94/09/02	REV: BE100106
APPROVAL		DATE: 94/09/02	REV: BE100106

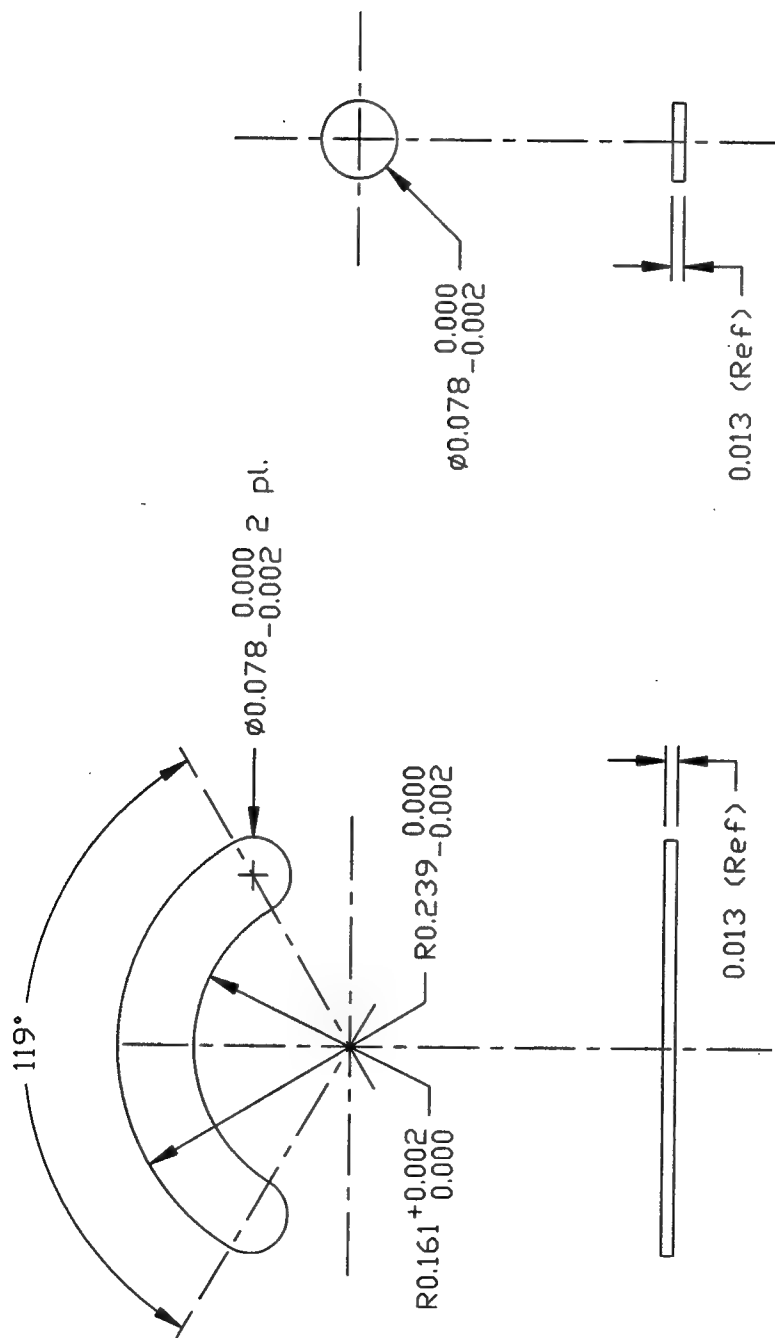


tree

TITLE: SHAFT, R SENSOR

SCALE: 8:1 DATE: 94/09/08  
 No. BE 100107  
 RELEASE DATE:  
 94/09/08  
 DRAWN BY: J. K. BROWN  
 PROJECT: Actuators II  
 APPROVAL  
 FILE NAME: cbsnor4

Unless otherwise specified  
 dimensions are in inches  
 Tolerances on angles & or  
 decimals: .XX ± .01, .XXX ± .002  
 Hole Trest: N/A



-3 Detail

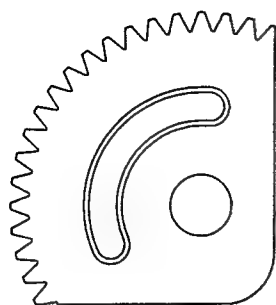
-5 Detail

1. Make from Glare Stop polarizing filter matl.  
Visual Pursuits, Inc.

tra

TITLE: POLARIZER ELEMENTS, HAND ACT	SCALE: 8:1	DATE: 94/09/23	REV: BE100108
DESIGN BY: J. K. BROWN	PROJECT: Actuators II	RELEASE DATE: 94/09/01	APPROVAL:
TEST: Mated	TEST: First: N/A	TEST: Second: N/A	TEST: Third: N/A

Unless otherwise specified,  
dimensions are in inches, and  
tolerances are as shown.  
Decimals .XX & .XXX & .000

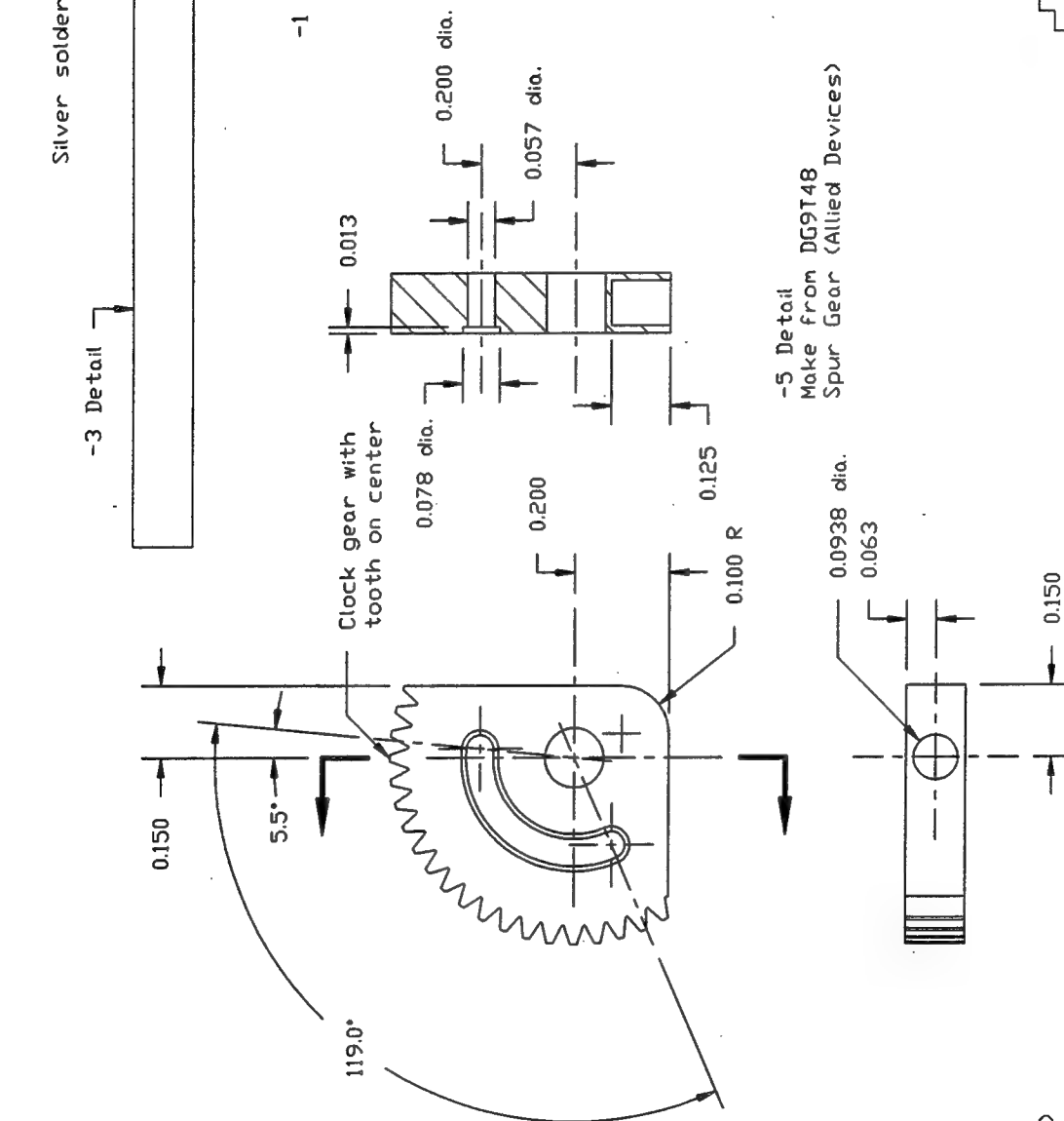


Silver solder

-3 Detail

-5 Detail

-1 Assembly



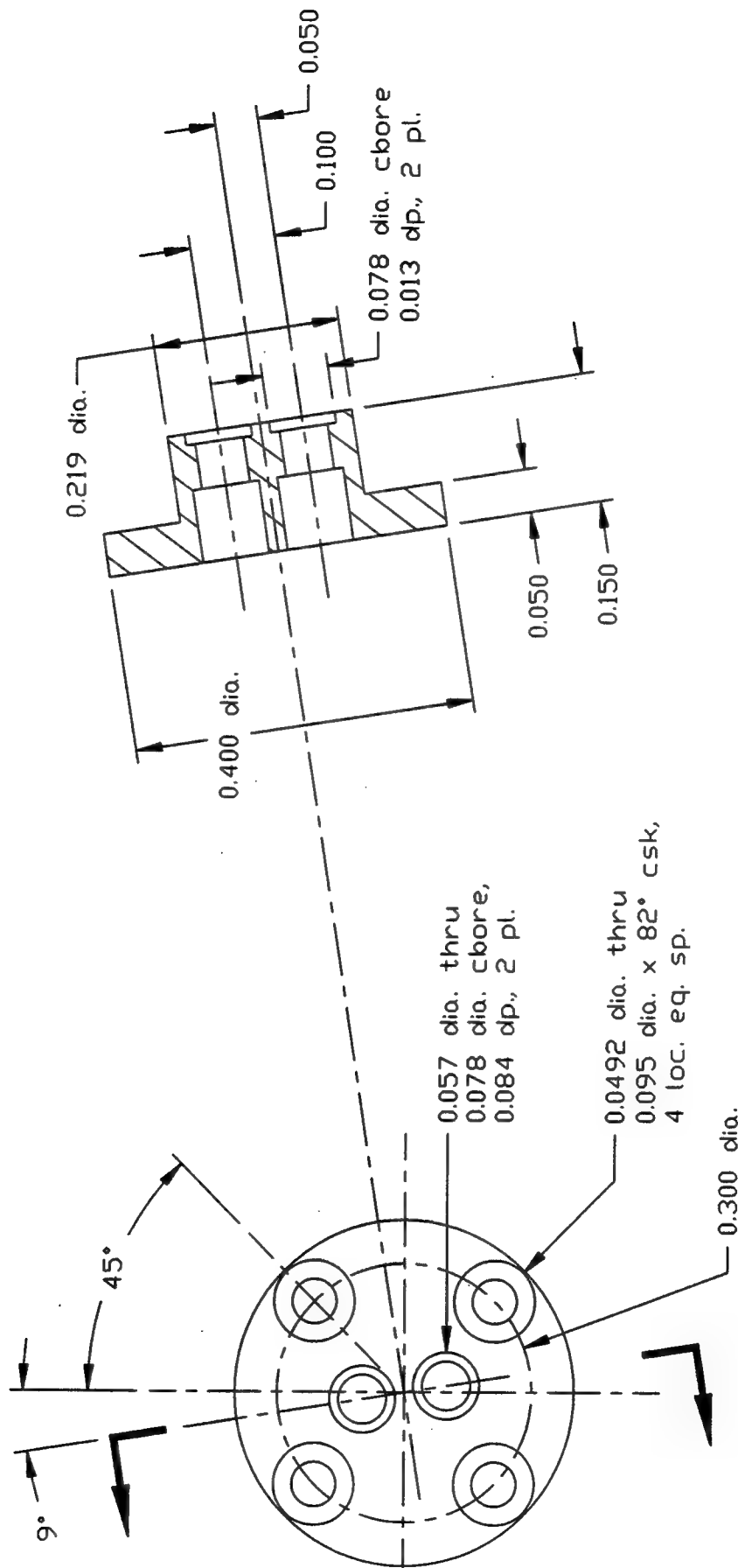
-5 Detail  
Make from DG9T48  
Spur Gear (Allied Devices)

-3 Detail  
Make from DWX-2-24  
Dowel Pin (Small Parts Inc.)

trc

TITLE	GEAR ARM, HAND ACTUATOR
SCALE	4:1
DATE	94/10/03
DRWN BY	J. K. Brown
PROJECT	Actuator's II
FILE NAME	Handact2.dwg
REVISION	
DATE	94/10/03
APPROVAL	

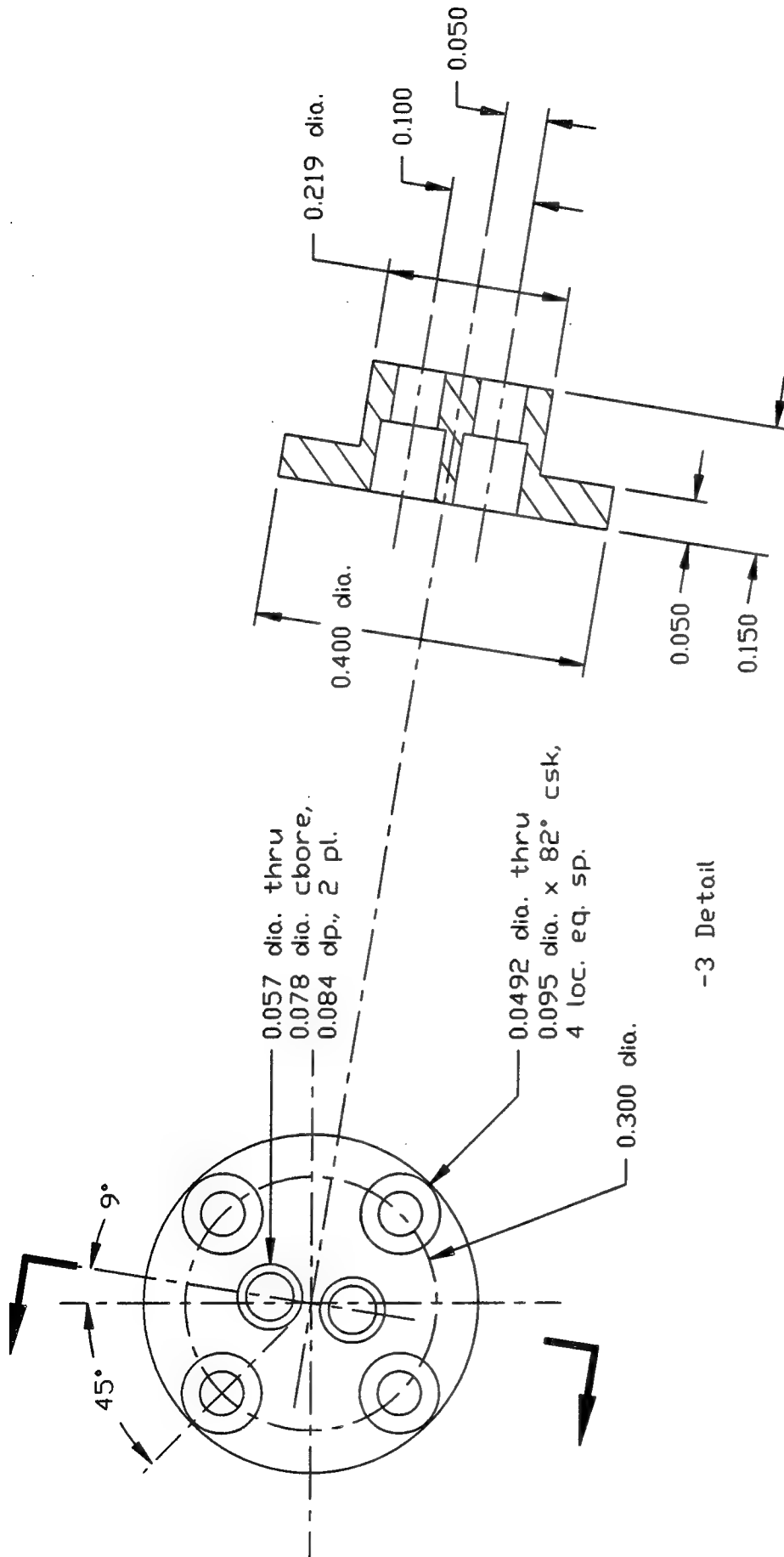
Unless otherwise specified  
Dimensions are in inches  
Tolerances on angles ± 0° 30'  
Decimals .XX ± .01, .XXX ± .002



-3 Detail

tra

DIODE ADAPTER, HAND ACTUATOR			
DATE: 8/1	DATE: 94/10/06	DATE: 94/10/06	DATE: 94/10/06
SCALE: 8/1	SCALE: 8/1	SCALE: 8/1	SCALE: 8/1
DESIGN BY: J. K. Brown	DESIGN BY: J. K. Brown	DESIGN BY: J. K. Brown	DESIGN BY: J. K. Brown
PROJECT: Actuator II	PROJECT: Actuator II	PROJECT: Actuator II	PROJECT: Actuator II
FILE NAME: handact14	FILE NAME: handact14	FILE NAME: handact14	FILE NAME: handact14



-3 Detail

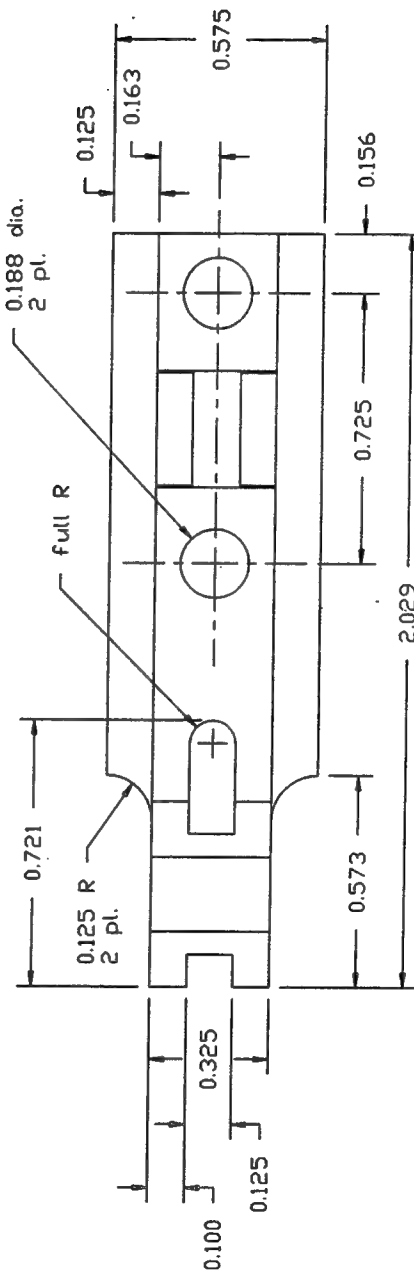
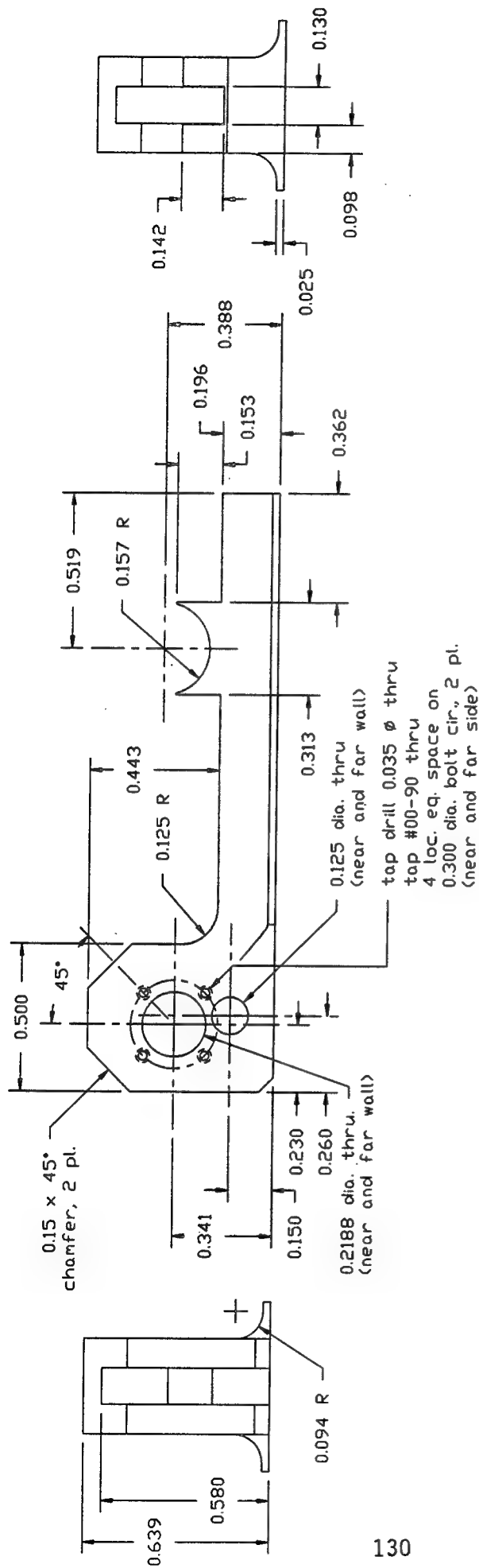
trc

TITLE: DETECTOR ADAPTER, HAND ACT.		NO. BE100112
SCALE: 8:1	DATE: 94/10/06	RELEASE DATE:
DESIGN BY: J. K. BROWN		94/10/06
PROJECT: ACTUATOR II		APPROVAL:
FILE NAME: handact15		

Unless otherwise specified,  
dimensions are in inches.  
Tolerances on angles ± 0.30°  
SURF. FIN. 12.5 μin. 1000



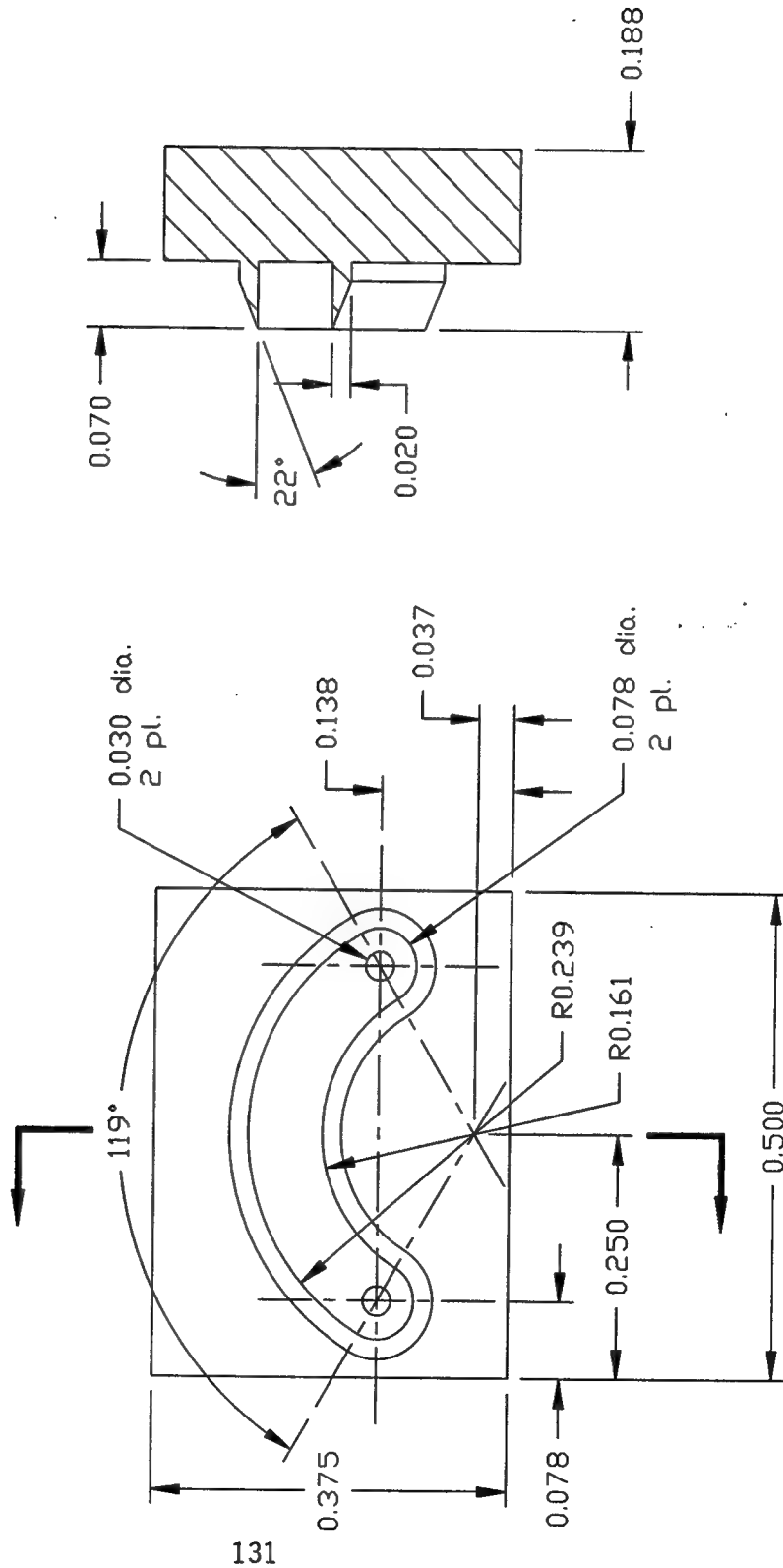




-3 Detail

trc

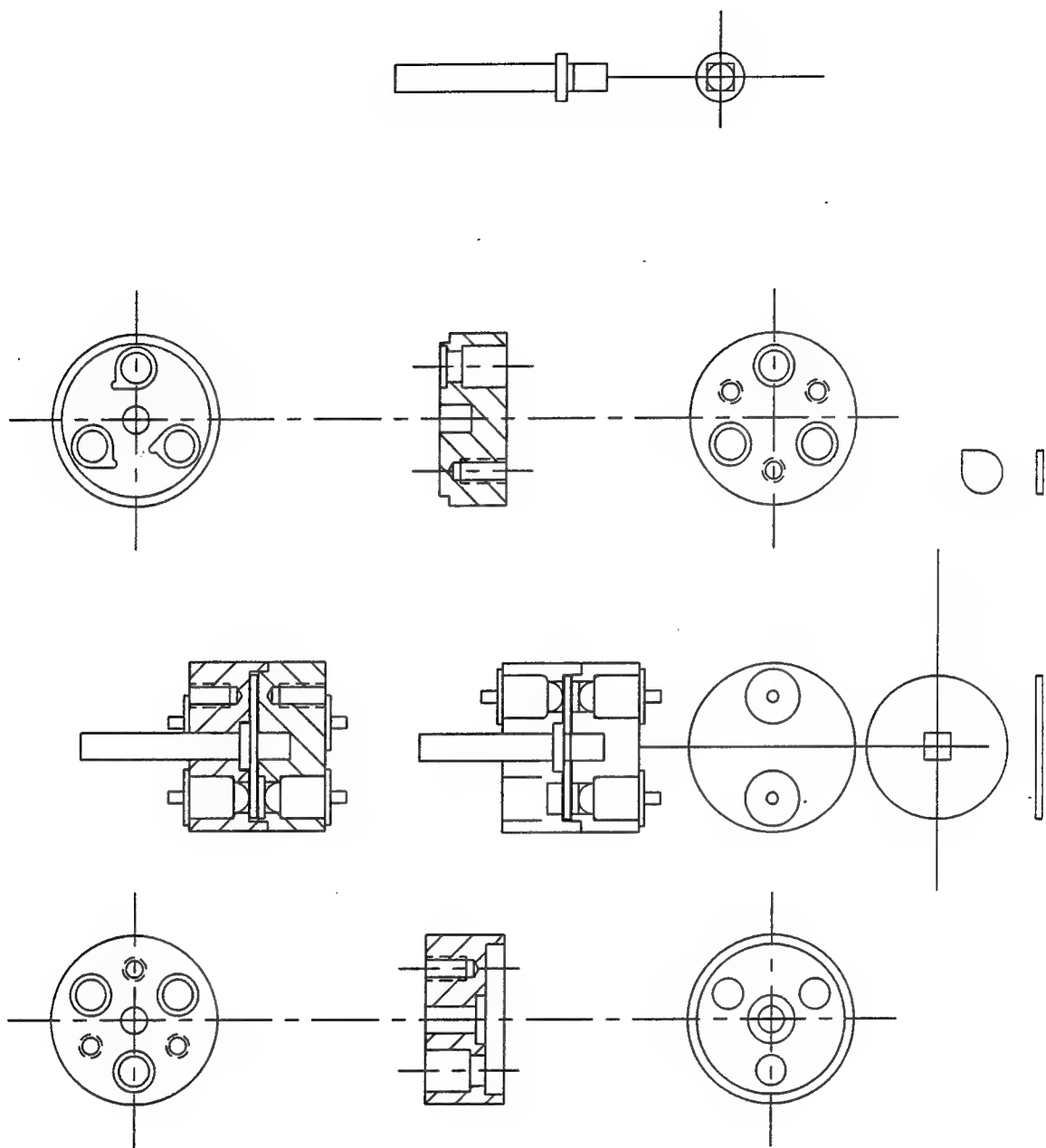
TITLE: HOUSING, HAND ACTUATOR			
SCALE: 3:1	DATE: 94/10/10	NO: BE100114	RELEASE DATE: 4/10/10
DRAWN BY: J. K. BROWN		PROJECT: Actuators II	
Math: 5051-15 AI		FILE NAME: handact17.dwg	
Revis: 10/10/10		APPROVAL	

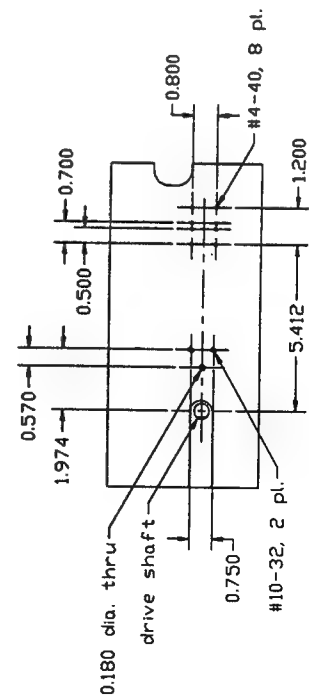


131

tre

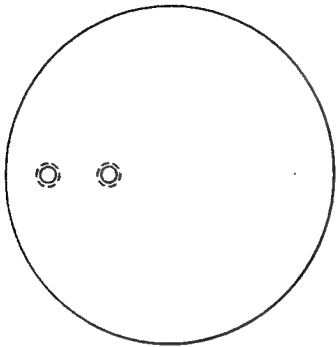
TITLE: DIE, POLARIZER ELEMENT		NO. BE-100116
SCALE: 8:1	DATE: 94/10/26	RELEASE DATE: 94/10/26
DRAWN BY: J. K. BROWN	PROJECT: ACTUATOR II	APPROVAL:
MATERIAL: Steel	FILE NAME: Handset19	
UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES, DECIMALS XX & .XX, XX & .XX		
HOLE TOLERANCE: N/A		

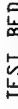


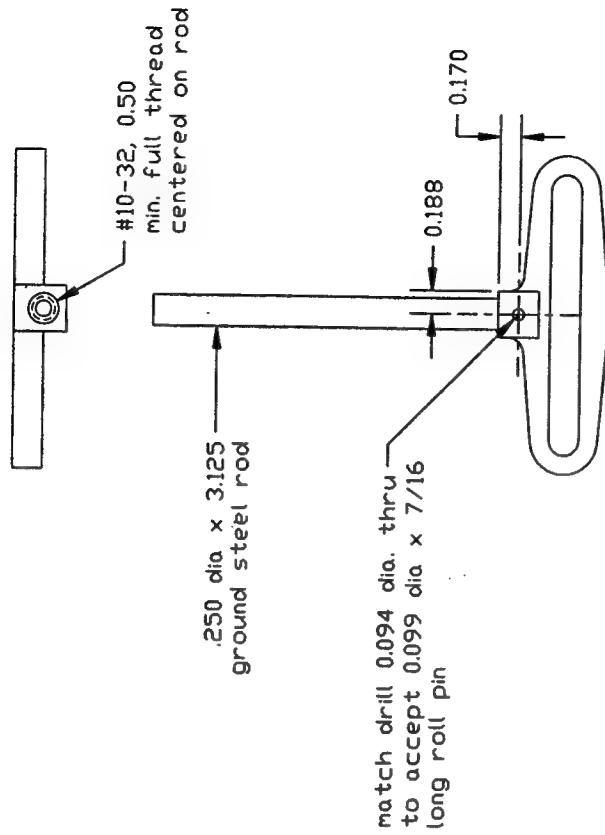


AT

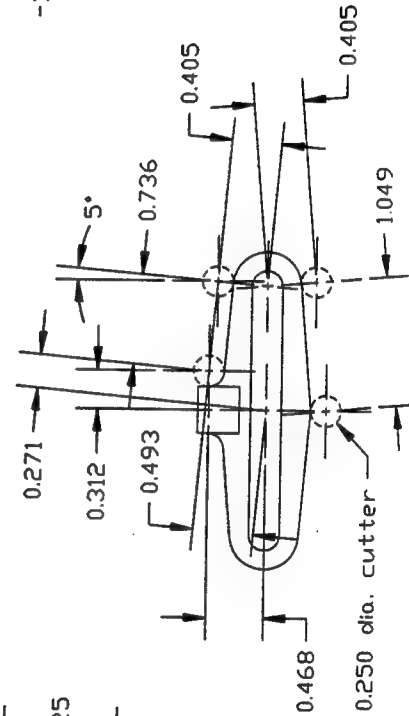
133



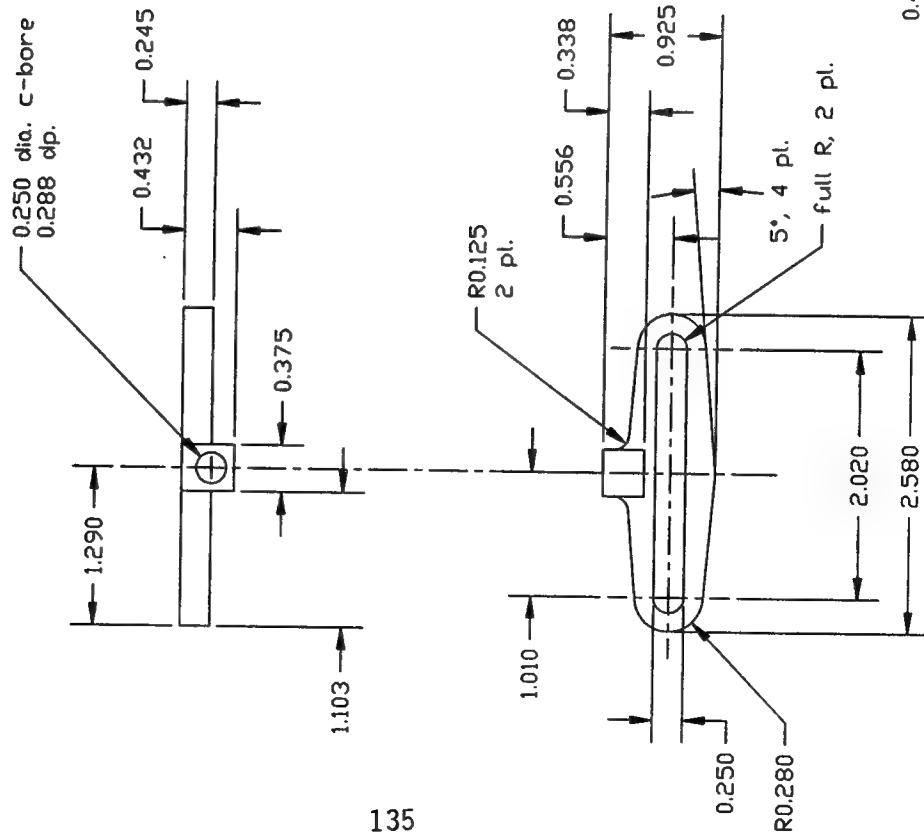
		TITLE: <b>CRANK, LMOTOR TEST BED</b>	
SCALE: <b>1:1</b>		DATE: <b>94/12/22</b>	
DRAWN BY: <b>J. K. Brown</b>		RELEASE DATE: <b>94/12/22</b>	
PROJECT: <b>ACTUATOR II</b>		APPROVAL:	
FILE NAME: <b>motor8.dwg</b>			



-1 Assembly



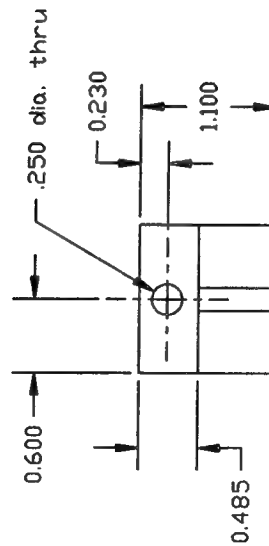
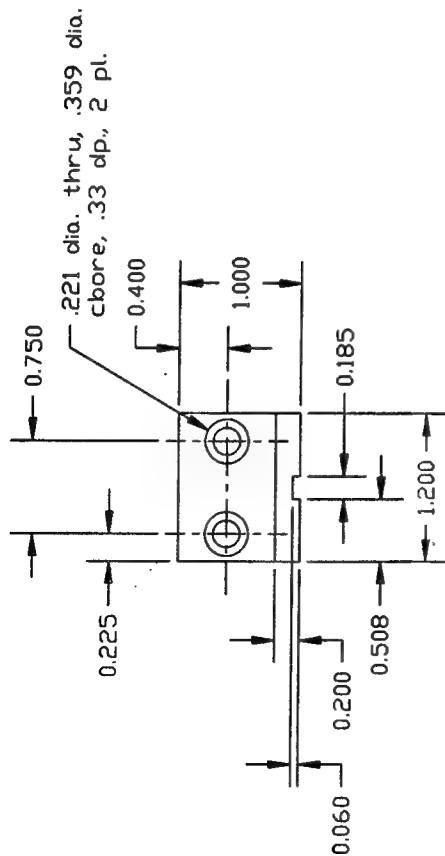
Supplemental View



-3 Detail

tra

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES FRACTIONS ARE TO BE IN DECIMALS DECIMALS ARE TO BE IN THOUSANDS	DATE 94/12/28	NO. BE100120
PROJECT ACTUATORS II	DESIGNER J. K. BROWN	RELEASE DATE 94/12/28
TEST TEST 1.1 N/A	FILE NAME 100120.dwg	APPROVAL

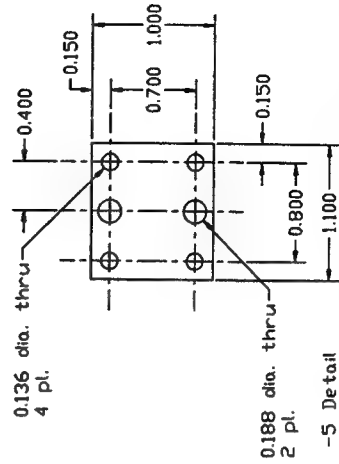
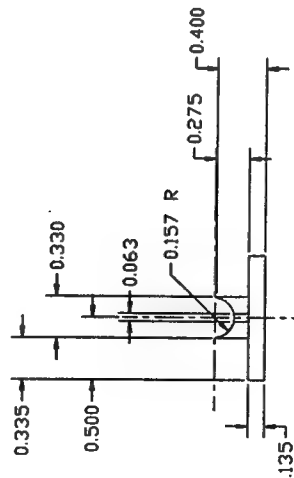
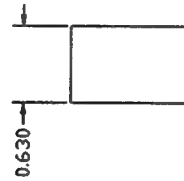
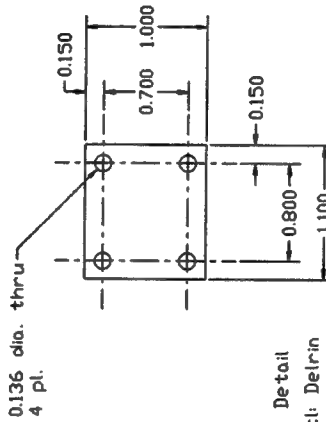
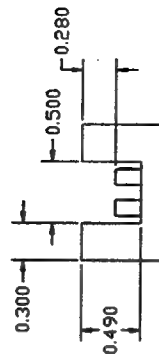
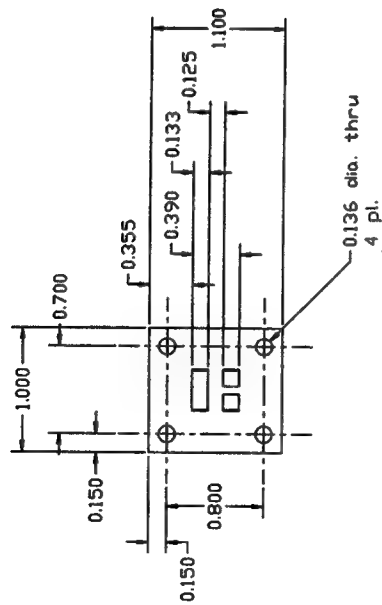
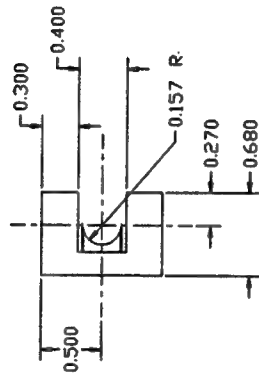
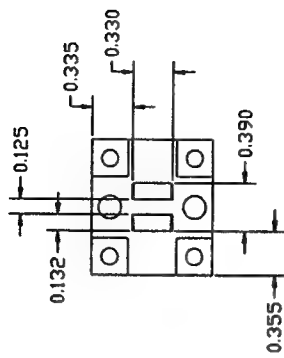


-5 detail  
Matl: 304 Cres

-3 detail  
Matl: 6061-T6 Al

trc

TITLE: DETAILS, L MOTOR TEST BED		SCALE: 1:1	DATE: 94/12/28	NO. BE100121
DRAWN BY: J. K. Brown		RELEASE DATE: 95/01/99		
PROJECT: Actuators II		APPROVAL:		
FILE NAME: motor100deg				



-5 Detail

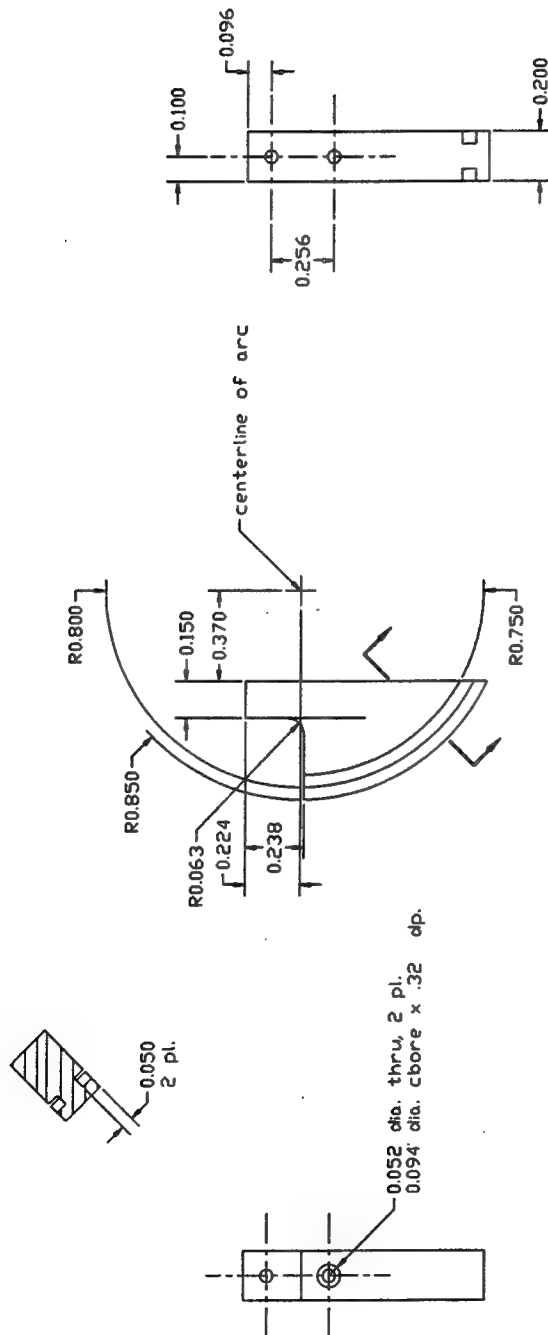
-7 Detail  
Matl: Delrin

-3 Detail

trc

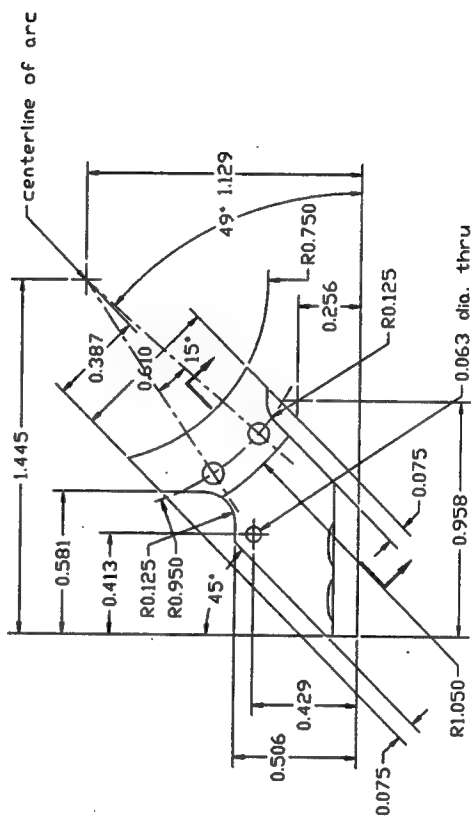
TITLE: MOUNT, LMOTOR TEST BED		DATE: 95/01/10	NO: BE100122
SCALE: 2:1		PROJECT: ACTUATOR II	APPROVAL:
DRAWN BY: J. K. BROWN		FILE NAME: Installing	
MATERIAL: 6061-T6 AL.			
FINISH: 125 ± 0.005			
UNLESS OTHERWISE SPECIFIED			
DIMENSIONS ARE IN INCHES			
TOLERANCES ARE AS SHOWN			
DECIMALS: .XX ± .005			
FRACTIONS: XX/64 ± .005			
ANGLES: XX° ± 1.0			

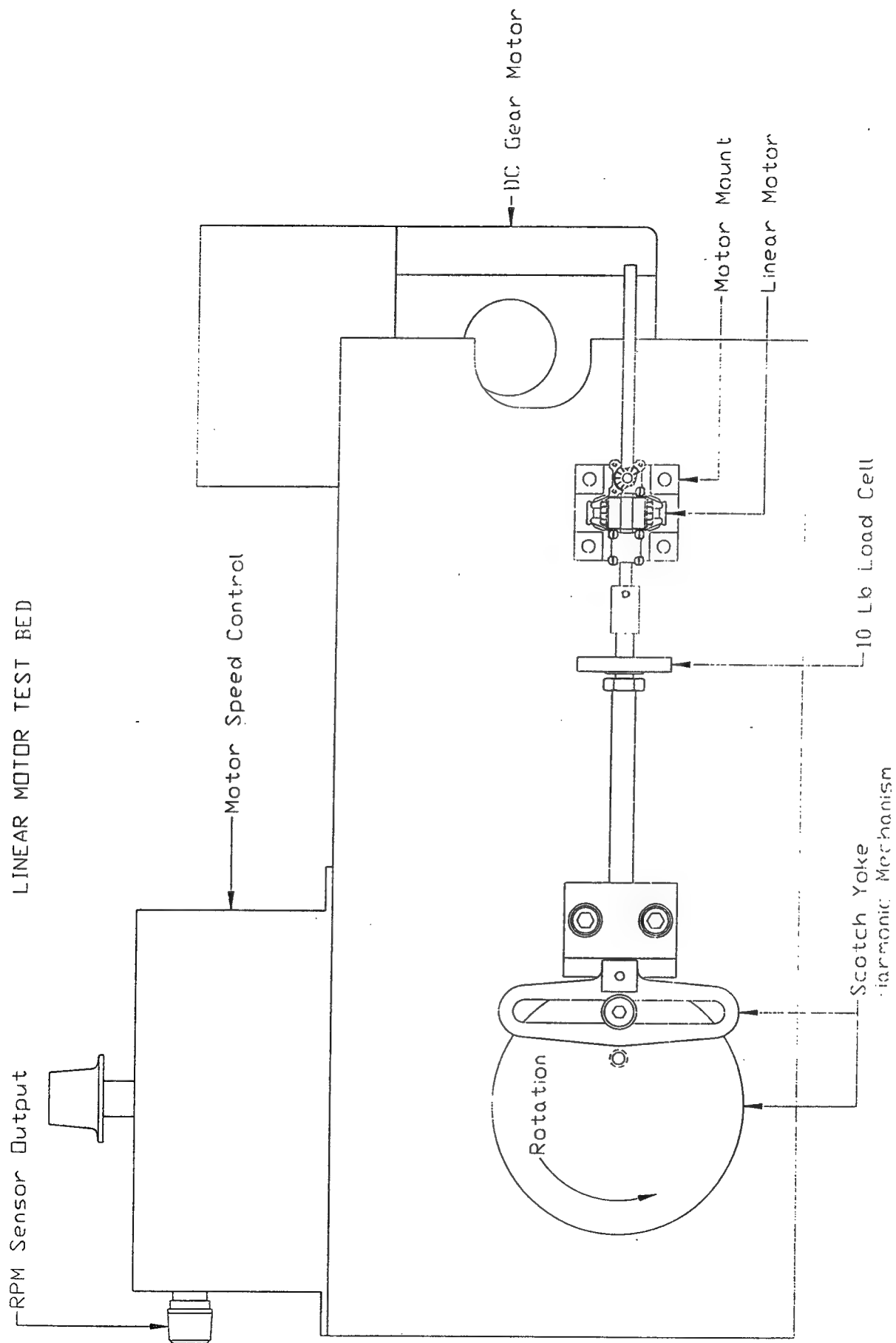




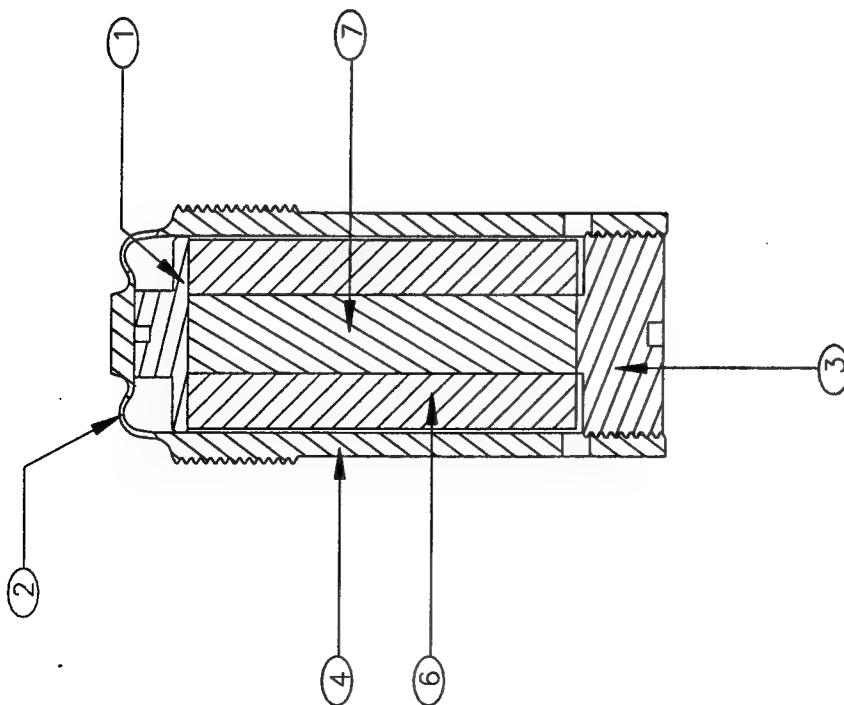
TRA

TITLE: CARRIER, L MOTOR MOUNT		SCALE: 4:1	DATE: 95/04/07	NO: BE100124
DRAWN BY: J. K. Brown		RELEAS DATE: 95/04/07		
PROJECT: Actuator's II		APPROVAL:		
FILE NAME: motor124.dwg				









3  
1 2

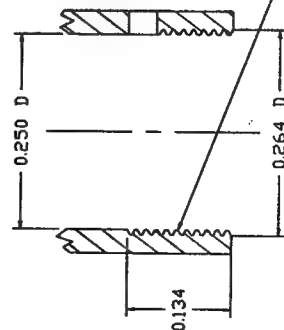
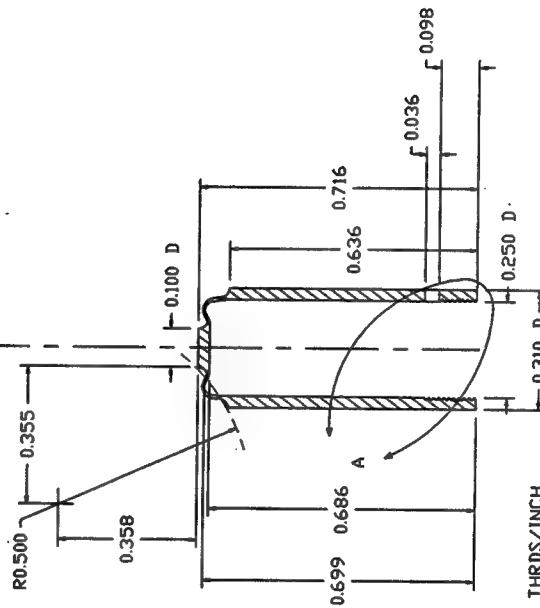
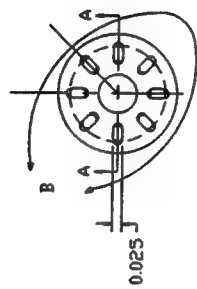
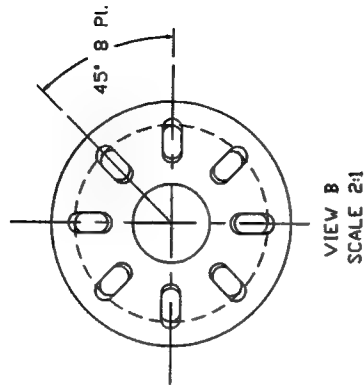
- ③ ETREMA, Ames, Iowa 1-800-327-7291
- ② MWS WIRE, Westlake Village, CA 818-991-8553
- ① Use BE000119 to wind coils

1	7	TRA P.O.- 7140-1	TERFENOL-D ROD	TERFENOL-D
1	6	TRA P.O.- 7169-2	COIL	MAG WRE, 30 G
1	5			
1	4	BE000112-3	HOUSING	---
1	3	BE000114-3	END CAP	---
1	2	BE000118-3	FLEXURE	---
1	1	BE000115-3	MAGNETIC RETURN PATH	---
---	---	BE000113	MOTIVE CELL ASSEMBLY	---
QTY REQD	ITEM NO.	PART NO.	DESCRIPTION	MAT'L/SPEC

## PARTS LIST

tra

Unless otherwise specified Dimensions are in inches Tolerances on angles ± 0°-30° Decimals .XX ± .02, .XXX ± .005	REV C	DATE: 2 Mar 94	FILE NAME: BE000113.DWG
PROJECT ACTUATOR II	DRAWN BY: A.P. Hilton	DATE: 10 Feb 93	APPROVAL:
PROJECT: MOTIVE CELL - ASSEMBLY			



VIEW A  
THREAD DETAIL  
SCALE 2:1

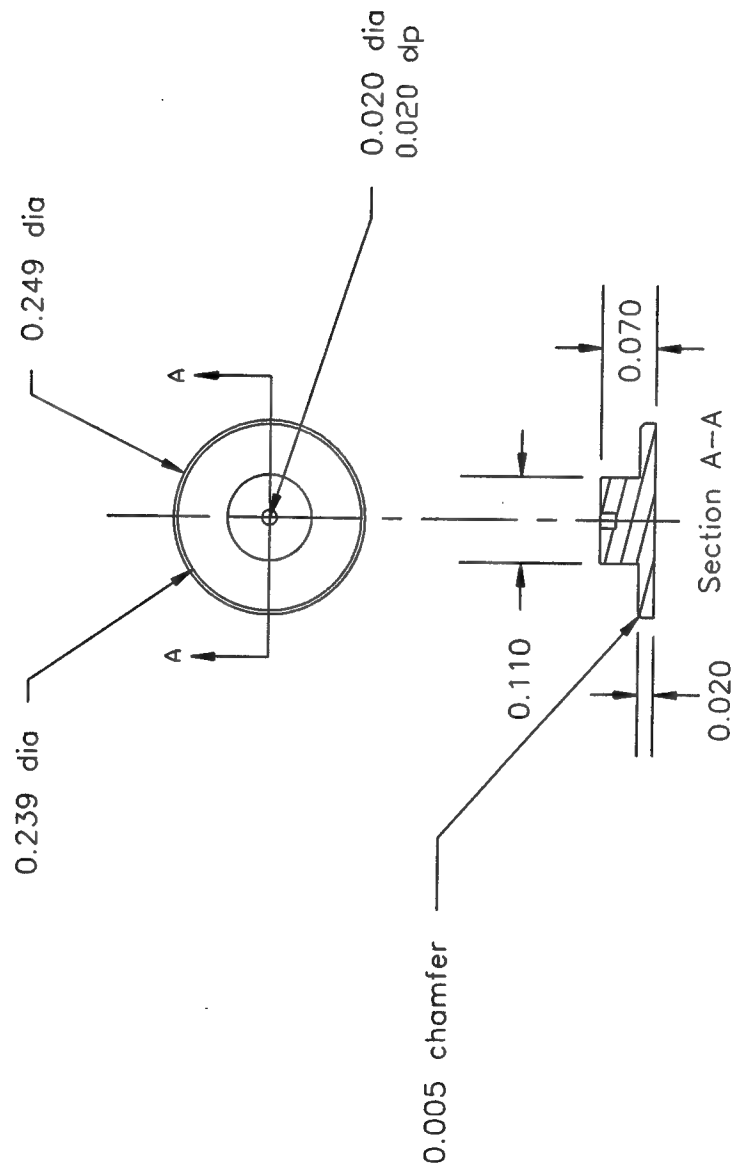
Section A-A

trc

TRC MOTIVE CELL

DESIGN: 2:1	DATE: 1 MAR 94	NO. BE00112
REV: B	APPROVED: APH	RELEASE DATE: 3 MAR 94
PROJECT: ACTUATOR II	FILE NAME: MOTIVE CELL.DWG	APPROVAL:





-3 Detail

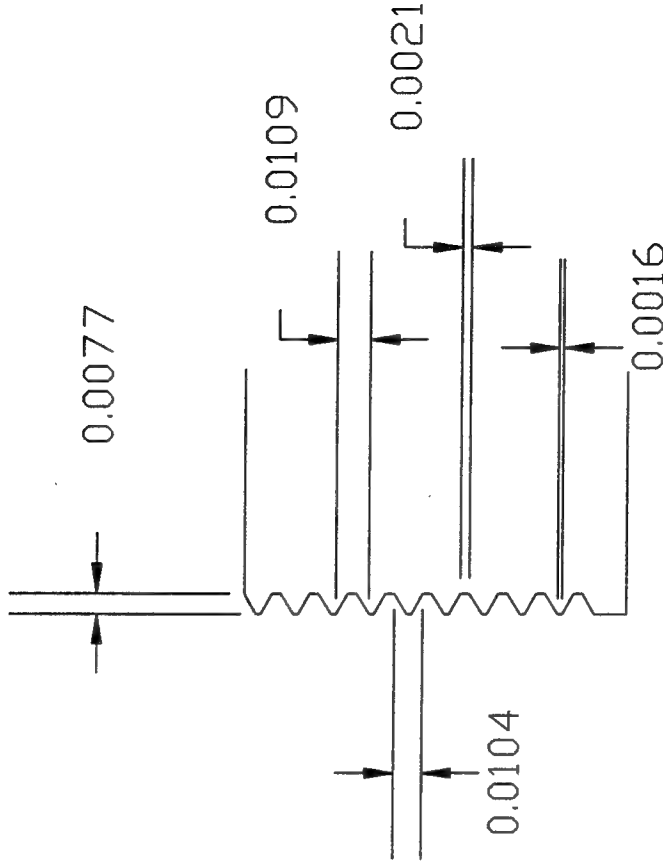
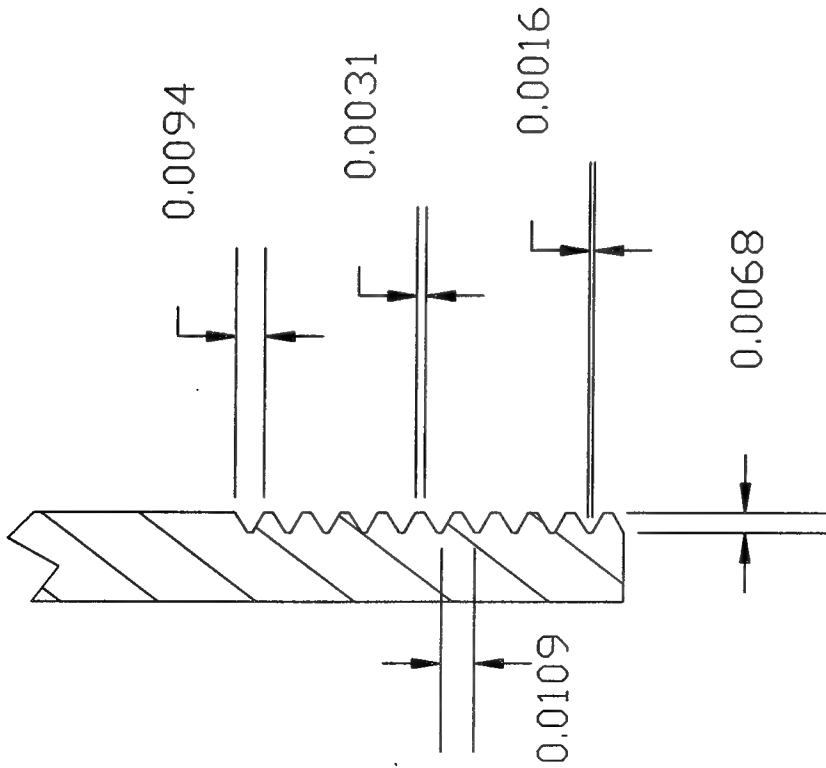
tr

TITLE: MAGNETIC RETURN PATH		REV A	DATE: 2 MAR '94	REV BE000015
SCALE: 4:1		APR	DATE: 2 MAR '94	REV BE000015
DRAWN BY: APH		PROJECT ACTUATOR II	FILE NAME: BE000015.DWG	APPROVAL
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE AS SHOWN		INCHES	FEET	INCHES
DECIMALS		XX	XX	XX



# INTERNAL THREADS

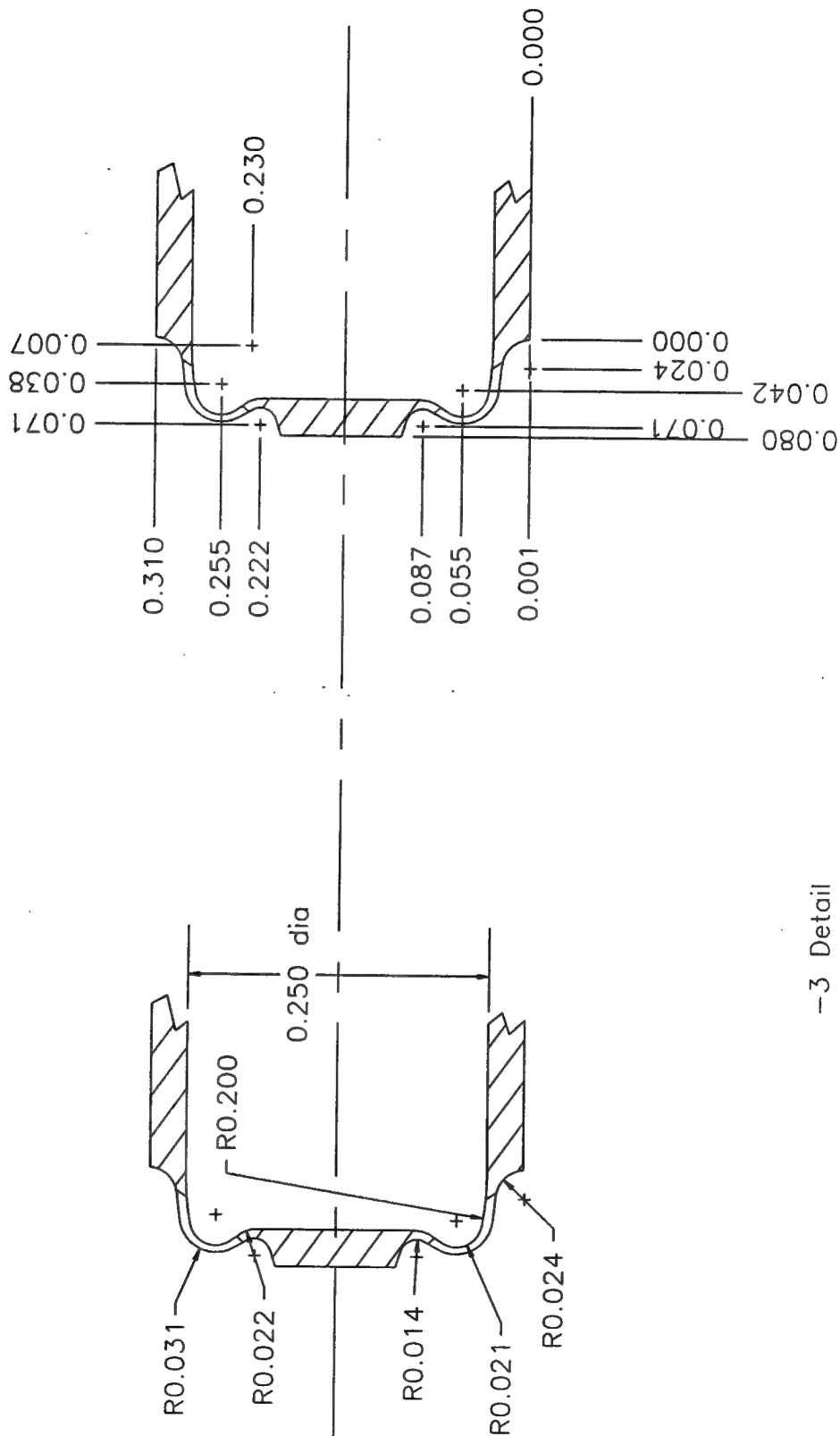
# EXTERNAL THREADS



80 THREADS/INCH

tr

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES ON ANGLES ± 0° 30'		REV A	DATE: 3 MAR 94	FILE: NAME: b000116.DWG
TOLERANCES ON ANGLES ± 0° 30'		REV A	DATE: 3 MAR 94	FILE: NAME: b000116.DWG
TOLERANCES ON ANGLES ± 0° 30'		REV A	DATE: 3 MAR 94	FILE: NAME: b000116.DWG
TOLERANCES ON ANGLES ± 0° 30'		REV A	DATE: 3 MAR 94	FILE: NAME: b000116.DWG
TOLERANCES ON ANGLES ± 0° 30'		REV A	DATE: 3 MAR 94	FILE: NAME: b000116.DWG
TOLERANCES ON ANGLES ± 0° 30'		REV A	DATE: 3 MAR 94	FILE: NAME: b000116.DWG
TOLERANCES ON ANGLES ± 0° 30'		REV A	DATE: 3 MAR 94	FILE: NAME: b000116.DWG
TOLERANCES ON ANGLES ± 0° 30'		REV A	DATE: 3 MAR 94	FILE: NAME: b000116.DWG
TOLERANCES ON ANGLES ± 0° 30'		REV A	DATE: 3 MAR 94	FILE: NAME: b000116.DWG
TOLERANCES ON ANGLES ± 0° 30'		REV A	DATE: 3 MAR 94	FILE: NAME: b000116.DWG



-3 Detail

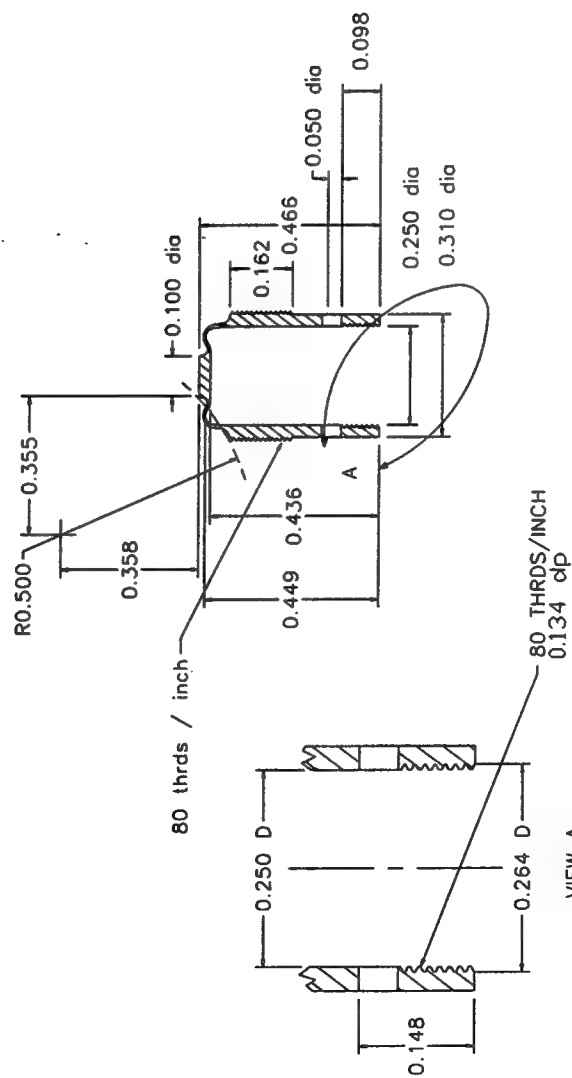
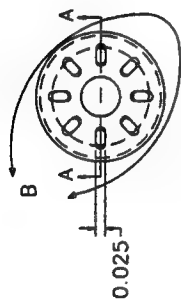
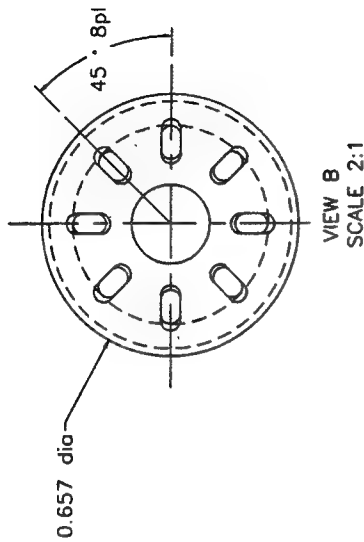
trc

FILE: FLEXURE DETAIL

SCALE: 7:1	DATE: 14 MAR 94	NO: BE000118
DESIGN BY: AP Hilton	PROJECT: ACTUATOR II	RELEASE DATE: 14 MAR 94
FILE NAME: be000118.dwg	APPROVAL:	

Unless otherwise specified  
Dimensions are in inches  
Tolerances on angles ± 30°  
Decimals .XX ± .02, .XXX ± .010

REV A  
MATERIAL: 4340 steel  
Heat Treat: XXX

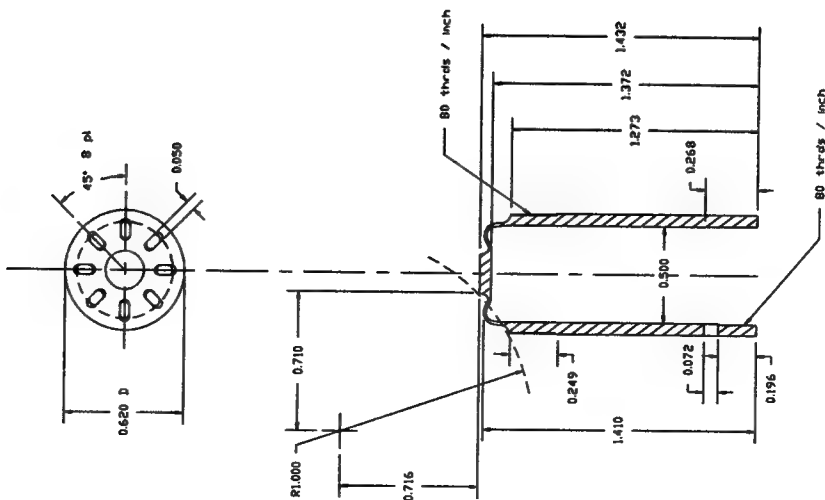
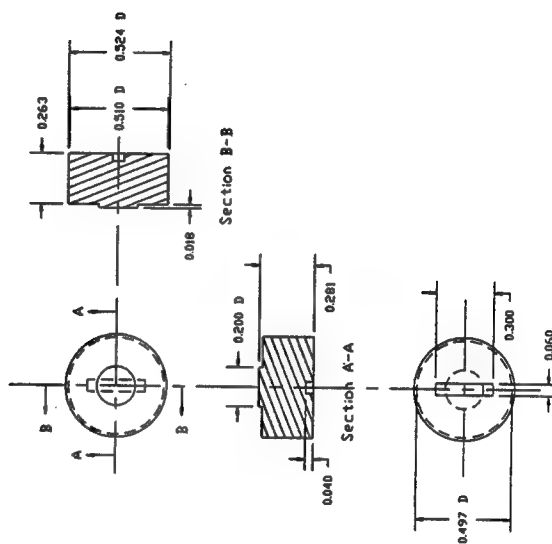
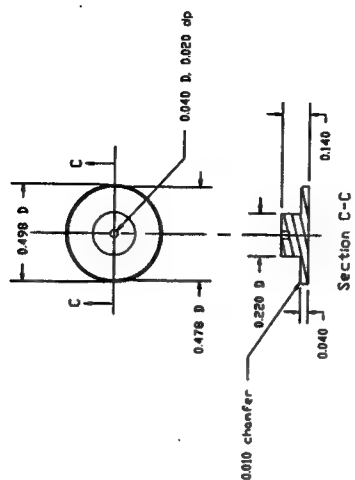


VIEW A  
THREAD DETAIL  
SCALE 2:1

Section A-A

tree

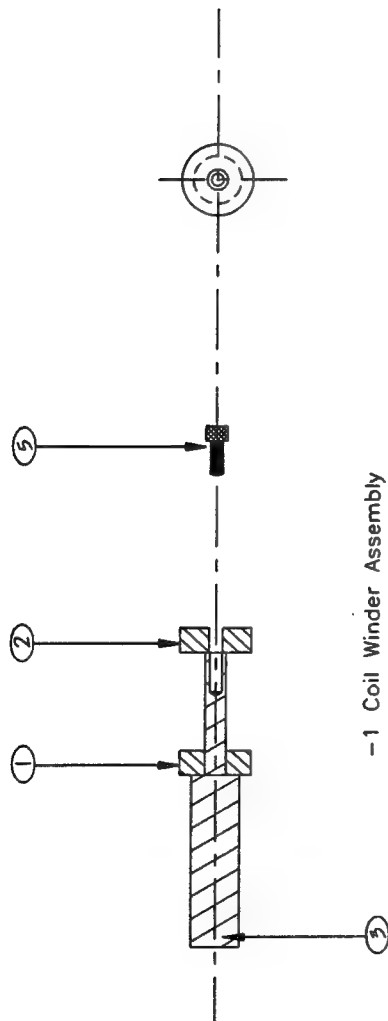
TITLE: MOTIVE CELL - 1/4" LONG		DATE: 16 Dec 94		No. BE00124	
SCALE: 2:1		DRAWN BY: AP Hilton		RELEASE DATE: Dec 94	
REV B		PROJECT: ACTUATOR II		APPROVAL:	
REV B		FILE NAME: be00124b.dwg			



trc

TRC Motive Cell; 1 inch

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE AS SHOWN DECIMALS XX ± 0.005 XX ± 0.005 XX ± 0.005	REV A	DATE 7 Jul 94	NO. BE 00139
PROJECT ACTUATOR II	DRAWN BY A. Hilton	RELEASE DATE:	XXK
FILE NAME: be00139.dwg	APPROVAL		



-1 Coil Winder Assembly

①

① Small Parts Inc., Miami Lakes, FL 305-557-8222

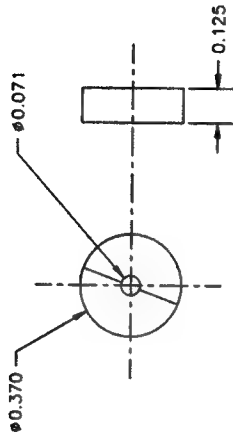
QTY REQD	ITEM NO.	PART NO.	DESCRIPTION	MAT'L/SPEC
1	6	XXX	XXX	---
1	5	Q-SHCX-172-4	1-72 x 1/4" HEX HD SCREW	SS
1	4	XXX	XXX	---
1	3	BE000119-3	WINDER CORE	---
1	2	BE000119-7	TEFLON WASHER	TEFLON
1	1	BE000119-5	TEFLON WASHER	TEFLON
---	---	BE000195	COIL WINDER ASSEMBLY	---

PARTS LIST

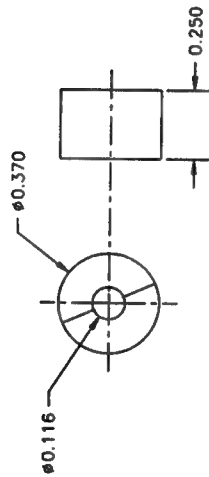
tr

TITLE: COIL WINDER ASSEMBLY	
SCALE: 1:1	DATE: 24 Feb 95
DESIGNED BY: AP Hilton	RELEASE DATE: XXX
PROJECT: ACTUATOR II	APPROVAL: XXX
FILE NAME: BE000195.dwg	

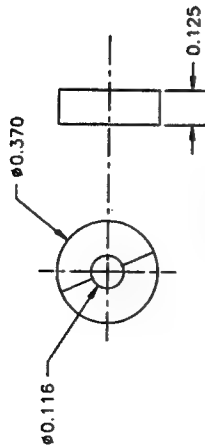
Unless otherwise specified  
Dimensions are in inches  
Tolerances are in inches  
Material: XXX  
Heat Treat: NO



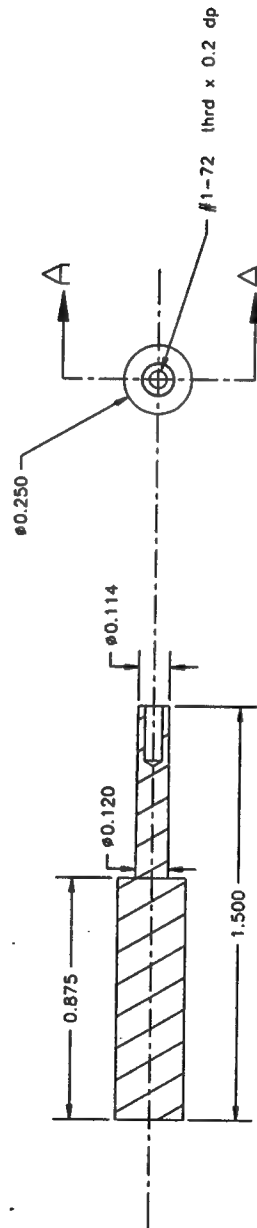
-9 Front Washer  
Mat'l: teflon



-7 Back Washer #2  
Mat'l: teflon



-5 Back Washer #1  
Mat'l: teflon



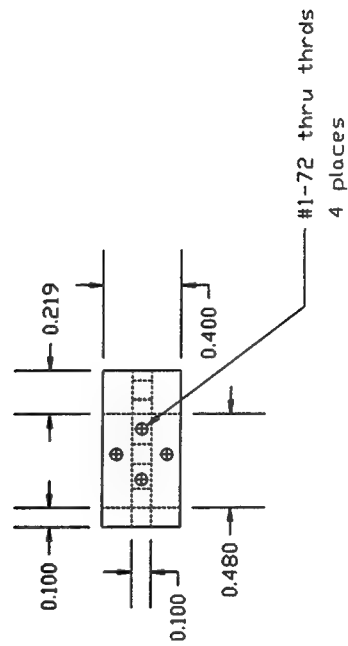
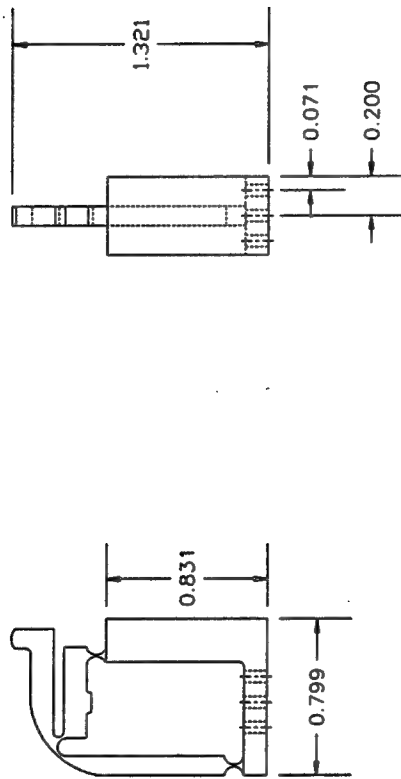
-3 Mandrel

1ra

TITLE: Detail; Coil Winder		No. BE000119
SCALE: 3:1	DATE: 17 Mar 94	RELEASE DATE: 3 Oct 95
DRAWN BY: A. P. Hilton		APPROVAL: C
PROJECT: Actuator II		FILE NAME: BE00119c.dwg
Rev C		
Mat'l: Steel		
Heat Treat:		

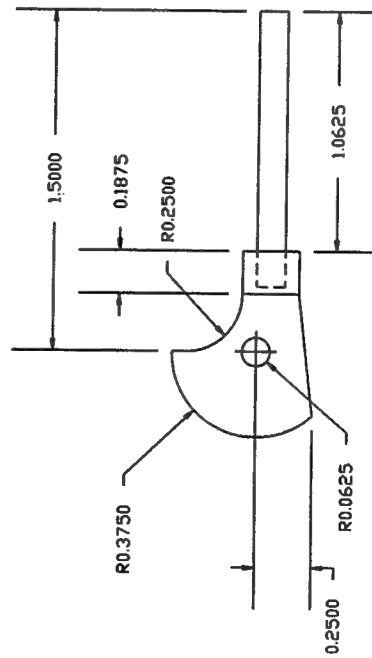
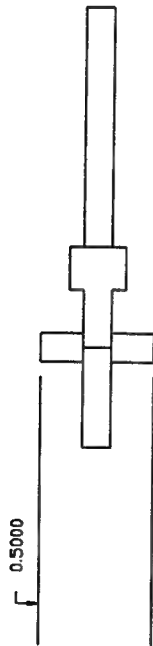
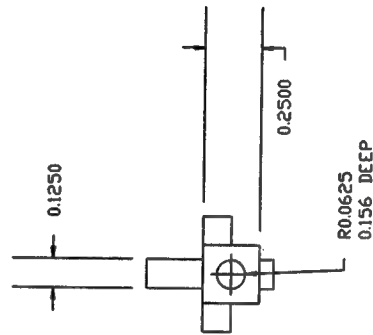
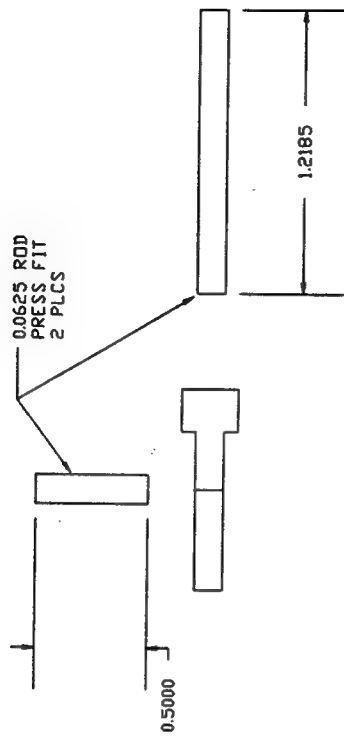
Unless otherwise specified:  
Dimensions are in inches  
Tolerances on angles  $\pm 0^\circ 30'$   
Decimals .XX  $\pm .03$ , .XXX  $\pm .005$

See BE00127 for details



trc

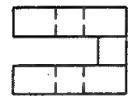
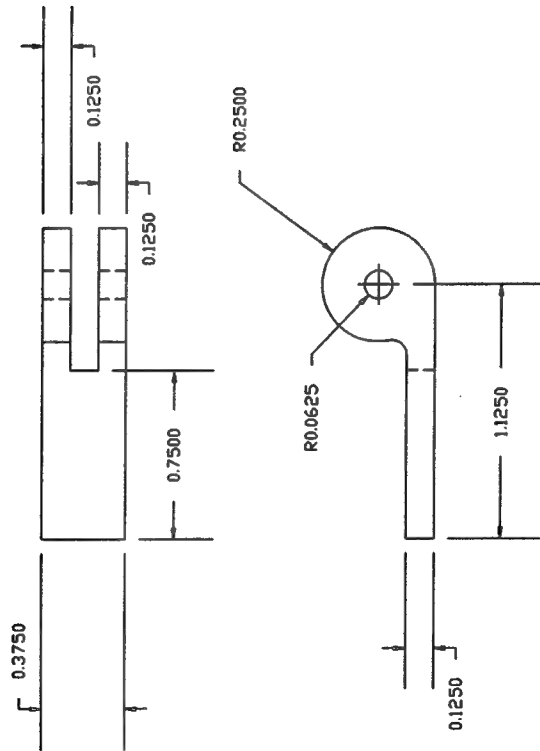
Title: Deflection Magnifier		Scale: 1:1	Date: 9 May 94	Rev: BE00126
Unless otherwise specified, dimensions are in inches. Tolerances on angles ± 0° 30'. Decimals .XX ± .00, .XXX ± .001.		Drawn By: AP Hilton	Project: Actuator II	Release Date: XXX
REV A		Heat Treat: Steel	Heat Treat: XXX	Approval
		File Name: BE00126.dwg		



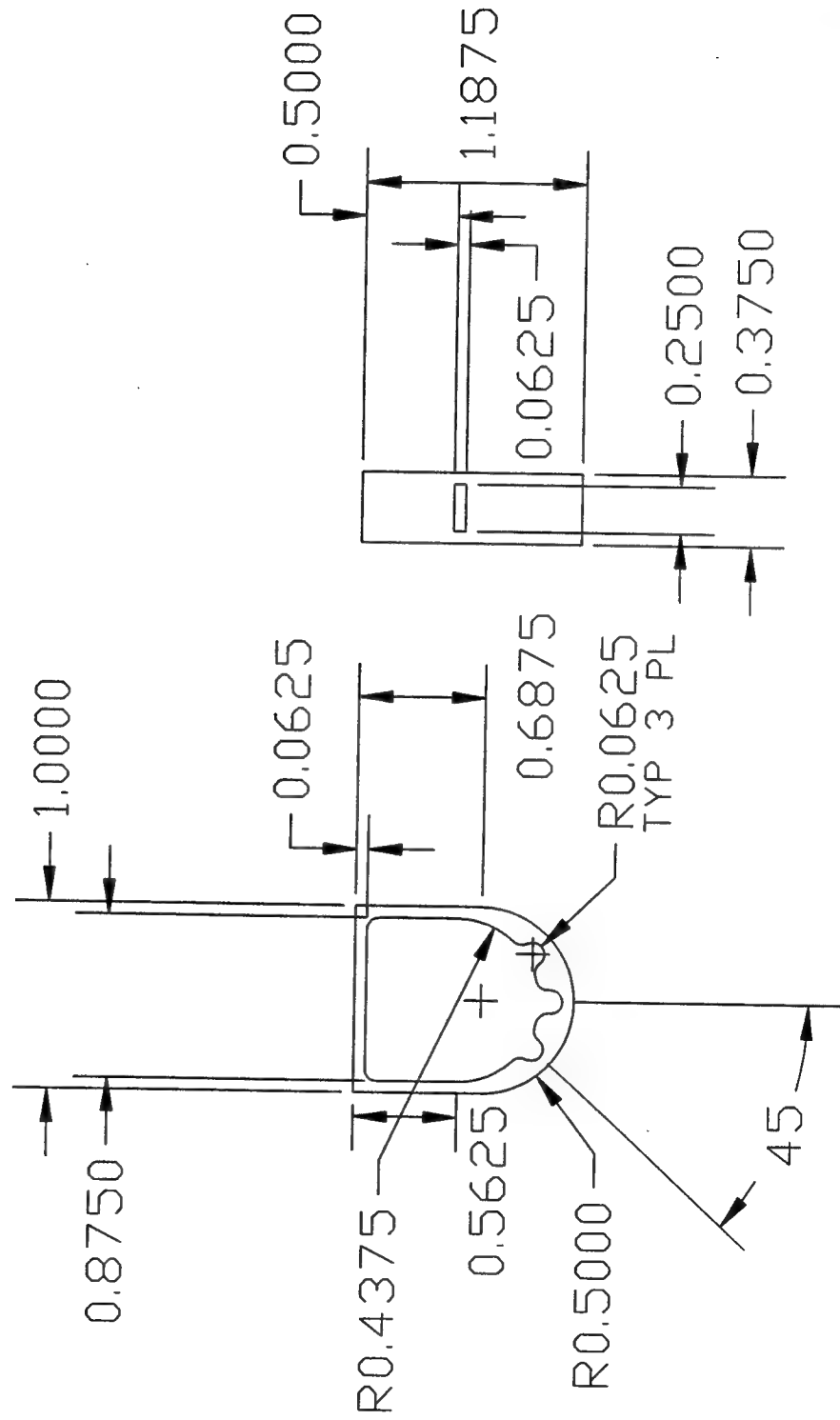
tra

TITLE:	CAM
SCALE:	NTS
DATE:	11/12/93
NO.:	100300
DRAWN BY:	RR.GOODWIN
PROJECT:	AS 100300 II
REV:	C
FILE NAME:	100300.DWG



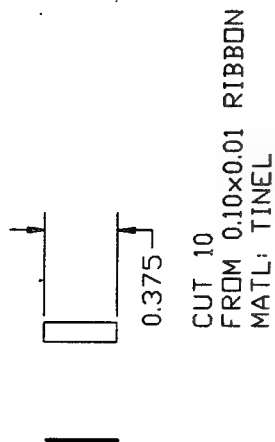


TITLE:	TRUNION
SCALE:	
DATE:	11/12/93
NO.:	100301
DRAWN BY:	R.R.GOODWIN
PROJECT:	ACTIVATOR II
FILE NAME:	100301.DWG
REV:	C

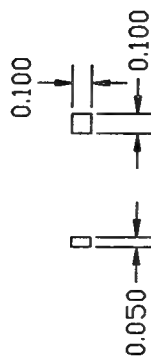


trc

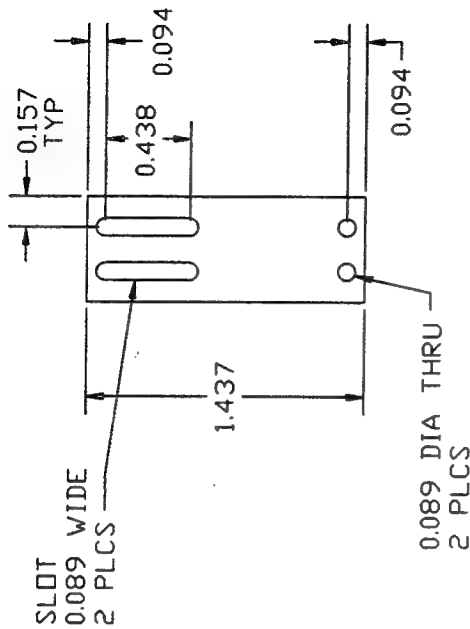
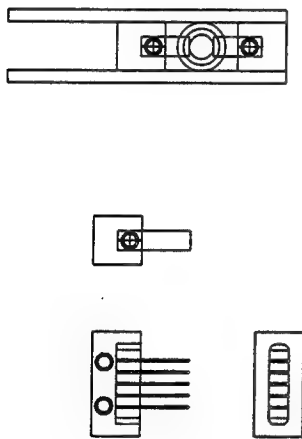
TITLE:	FINGER ATTACHMENT	REV:	100302
SCALE:	1:1	DATE:	1/7/94
DRAWN BY:	R.R.GOODWIN	REV:	A
PROJECT:	ACT 100 TOP 11		
FILE NAME:	100302.DWG		



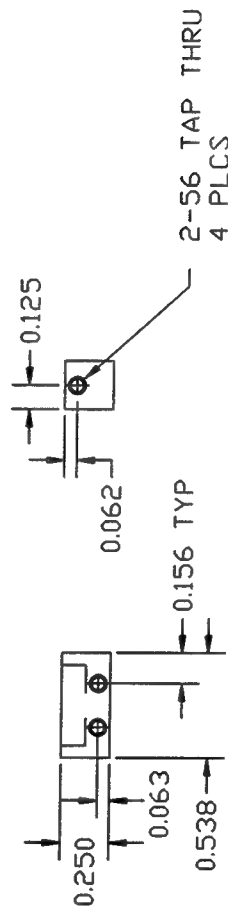
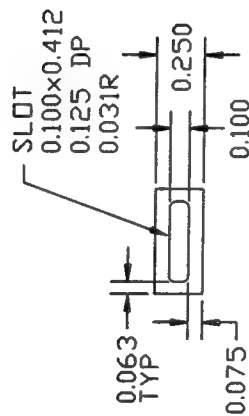
FEET (10)



SPACER (12)



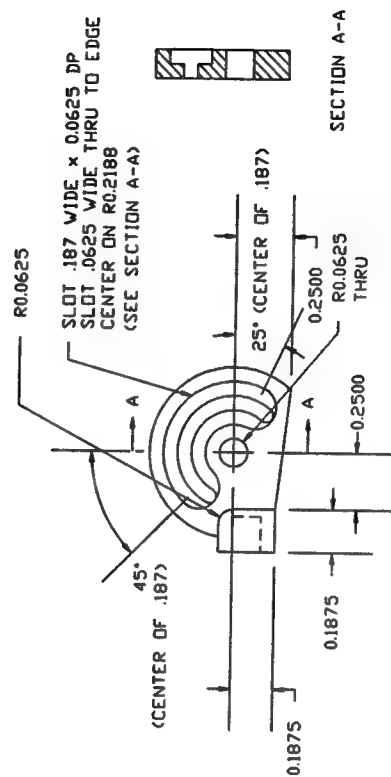
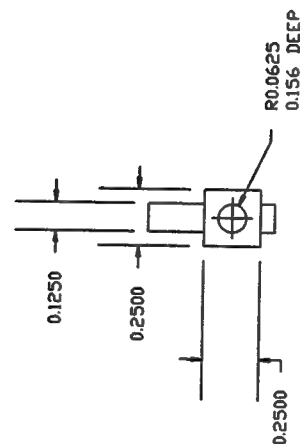
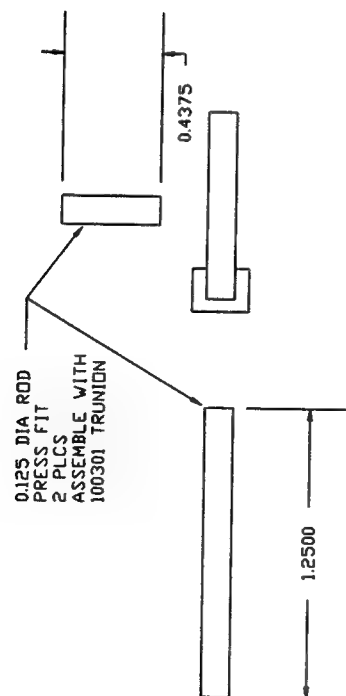
SIDES (2)

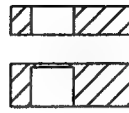


BODY (2)

tr2

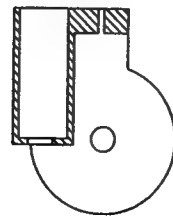
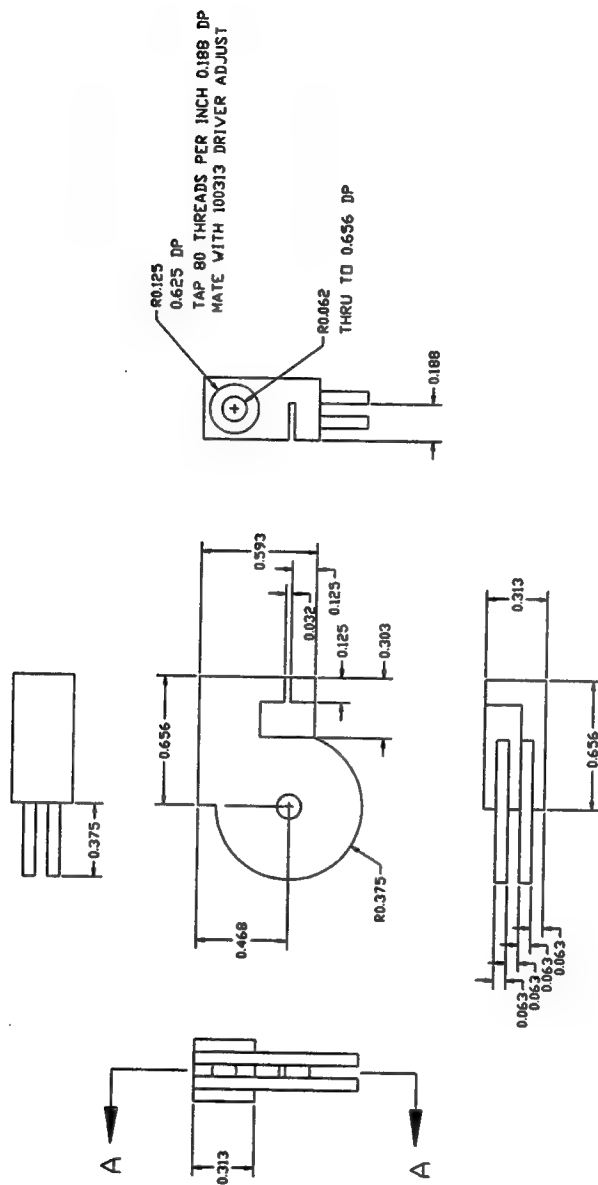
CRAWLER ASSY			
THUS: 1:1	DATE: 2/23/94	NO: 100303	RELEASE DATE:
SCALE: 1:1	DATE: 2/23/94	NO: 100303	RELEASE DATE:
DESIGN BY: GOODWIN	PROJECT ACTUATOR II	FILE NAME: 100303.DWG	APPROVAL:
DESIGN BY: GOODWIN	PROJECT ACTUATOR II	FILE NAME: 100303.DWG	APPROVAL:





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SECTION A-A

tra

TITLE: DRIVER HOUSING

SCALE: 1:1 DATE: 3/30/94

100307

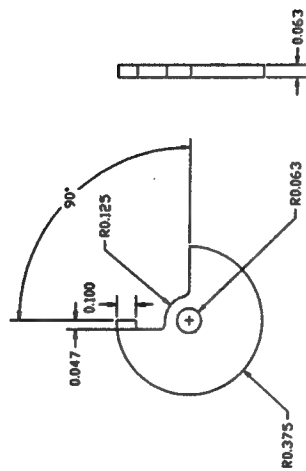
RELEASE DATE:

DRAWN BY: GOODWIN

PROJECT: ACTUATOR II

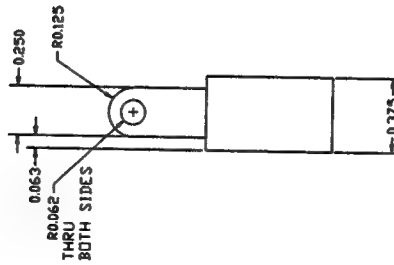
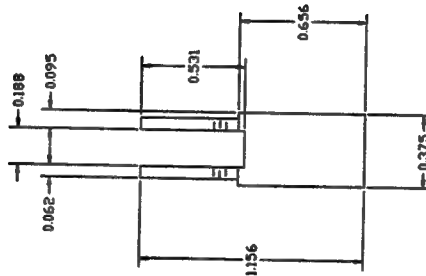
FILE NAME: 100307.DWG

Unless otherwise specified  
Dimensions are in inches ± .005  
Tolerances are in inches ± .005  
Materials: AL 6061-T6

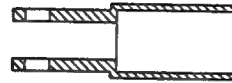


tra

TITLE: STEPPER		DATE: 3/30/94	NO: 100308
SCALE: 1:1	DRAWN BY: GOODWIN	PROJECT: ACTUATOR II	RELEASE DATE: XXX
UNLESS OTHERWISE SPECIFIED: TOLERANCES ON DIMENSIONS: TOLERANCES ON ANGLES: 0°-30° DECIMALS: .XX ± .02, .XXX ± .010		FILE NAME: 100308.DWG	APPROVAL:



R0.156  
THRU TO 0.625 DP  
TAP 80 THREADS PER INCH 0.188 DP  
MATE WITH 100311 CLAMP ADJUST

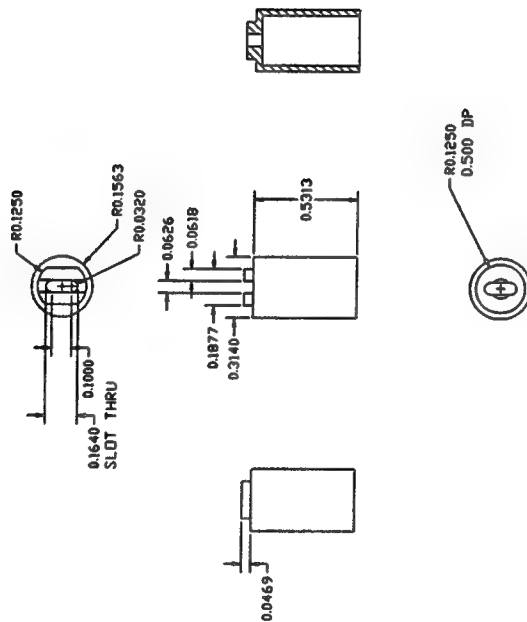


tr2

TITLE CLAMP HOUSING

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON ANGLES ± 0° 30' DECIMALS XX ± 0.01, XXX ± 0.005	SCALE 1:1	DATE 3/30/94	NO. 100309
DESIGNED BY: GOODWIN	DATE 3/30/94	RELEASE DATE:	XXX
PRODUCED BY: ACTUATOR II	DATE 3/30/94	APPROVAL	XXX
FILE NAME: 100309.DWG	DATE 3/30/94	APPROVAL	XXX

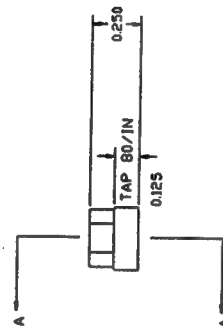
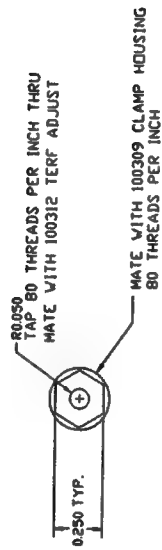




tr2

TITLE: PASSIVE CLAMP			
SCALE: 1:1	DATE: 3/30/94	NO: 100310	RELEASE DATE:
DRAWN BY: GOODWIN		XXX	APPROVAL:
PROJECT: ACTUATOR II			
THE NAME PSYCLUP			

Unless otherwise specified,  
 dimensions are in inches  
 Tolerances on angles ± 0° 30'  
 Decimals XX ± 0.01 XX ± 0.01



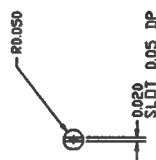
SECTION A-A

tre

FILE	CLAMP ADJUST	DATE	3/31/94	NO.	100311
SCALE	1:1	DATE	3/31/94	RELEASE DATE	XX
DESIGN BY	GOODWIN	PROJECT	ACTUATOR II	APPROVAL	
FILE NAME CLAMPADJUST					

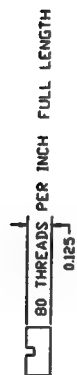
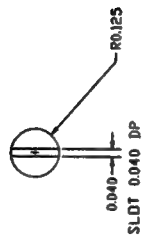
Unless otherwise specified  
 Dimensions are in inches  
 Tolerances on angles ± 0° 30'  
 Decimals XX ± .02, .XX ± .01

80 THREADS PER INCH  
 FULL LENGTH  
 MATE WITH 100311/100325 CLAMP ADJUST



tra

TRA		TERF ADJUST	
DATE	3/31/94	DATE	3/31/94
SCALE	1:1	SCALE	1:1
DESIGN NO.	GOODWIN	DESIGN NO.	GOODWIN
PROJECT	ACTUATOR II	PROJECT	ACTUATOR II
FILE NAME	TERFADJUST	FILE NAME	TERFADJUST
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON ANGLES ± 0° 30'		UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON ANGLES ± 0° 30'	
DECIMALS .XX ± .02 .XXX ± .010		DECIMALS .XX ± .02 .XXX ± .010	
APPROVAL		APPROVAL	
No. 100312		No. 100312	
RELEASE DATE:		RELEASE DATE:	



MATE WITH 100307/100316 DRIVER HOUSING

tra

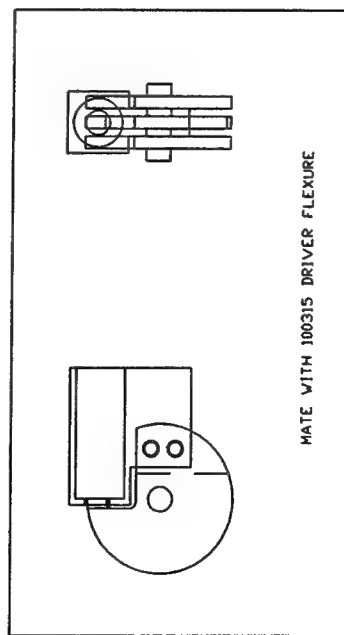
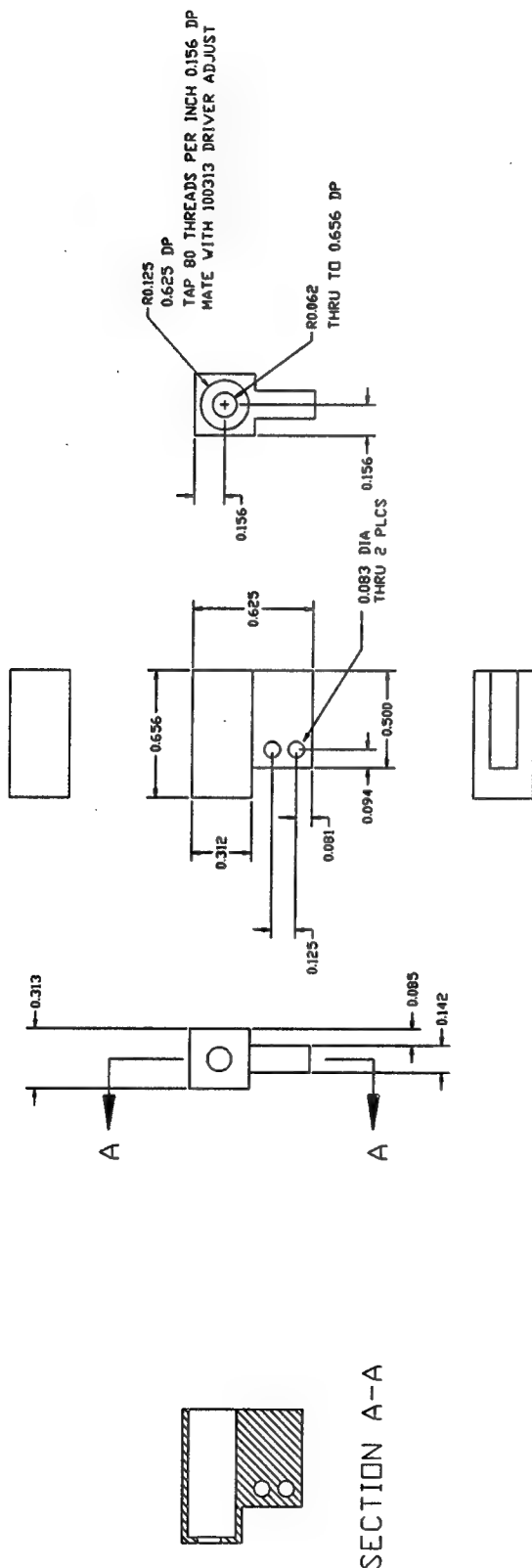
TITLE: DRIVER ADJUST		NO. 100313
SCALE: 1:1	DATE: 3/31/94	RELEASE DATE: XXX
DRAWN BY: GOODWIN		APPROVAL:
PROJECT: ACTUATOR II		FILE NAME: 100313.DWG

Unless otherwise specified  
Dimensions are in inches & are  
to be used as such.





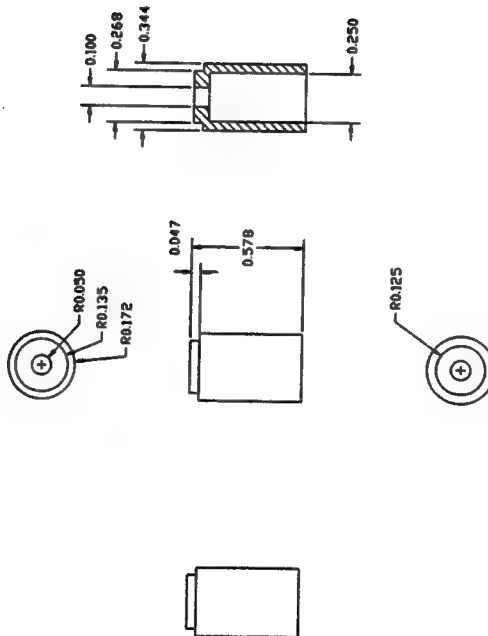
Unless otherwise specified:  
Dimensions are in inches  
Tolerances on angles  $\pm 0^\circ 30'$   
Decimals .XX  $\pm .03$  .XXX  $\pm .010$



trc

TITLE	FLEXURE DRIVER HOUSING
SCALE	1:1
DATE	4/5/94
DRAWN BY	GOODWIN
PROJECT	ACTUATOR II
FILE NAME	100316.DWG
APPROVAL	

Unless otherwise specified  
Dimensions are in inches  
Tolerances on angles ± 0° 30'  
Decimals .XX ± .02 .XXX ± .010

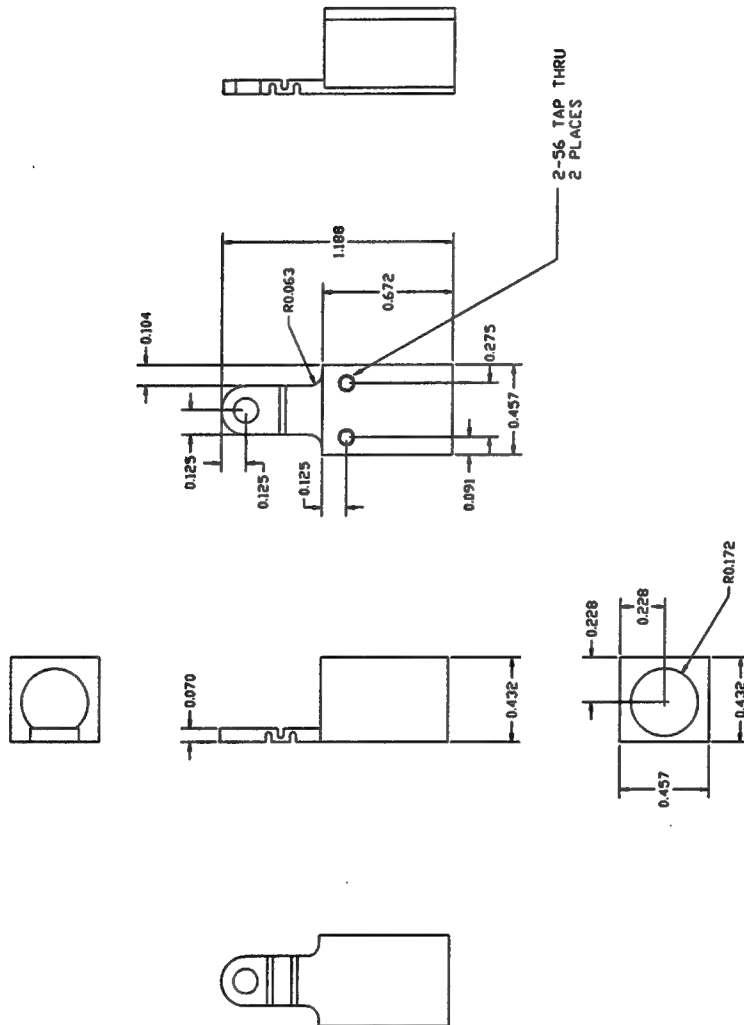


trb

TITLE: PASSIVE CLAMP			
SCALE: 1:1	DATE: 4/7/94	NO: 100317	RELEASE DATE:
DRAWN BY: GOODWIN		XX	
PROJECT: ACTIVATOR II		APPROVAL:	
FILE NAME: 100317.DWG			

Unless otherwise specified  
Dimensions are in inches  
Tolerances on angles & 0° 30'  
Decimals .XX & .00, .XX & .010

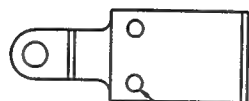
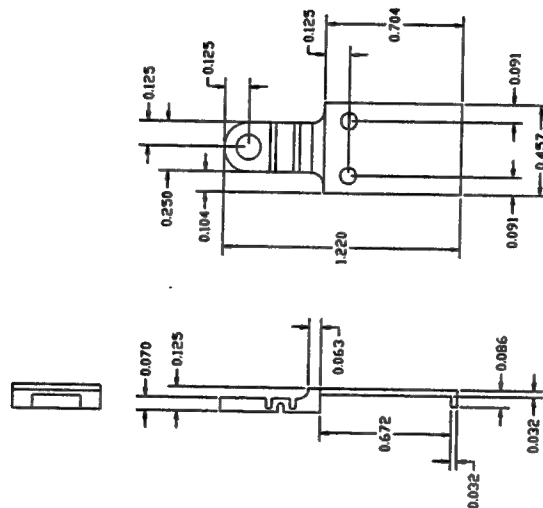




TRA

TITLE: CLAMP FLEX HOUSING RIGHT	SCALE: 1:1	DATE: 3/30/94	REV: 100318
			DESIGN DATE: XX
			DESIGN BY: GOODWIN
			PROJECT: ACTUATOR II
			FILE NAME: 100318.DWG
			APPROVAL:

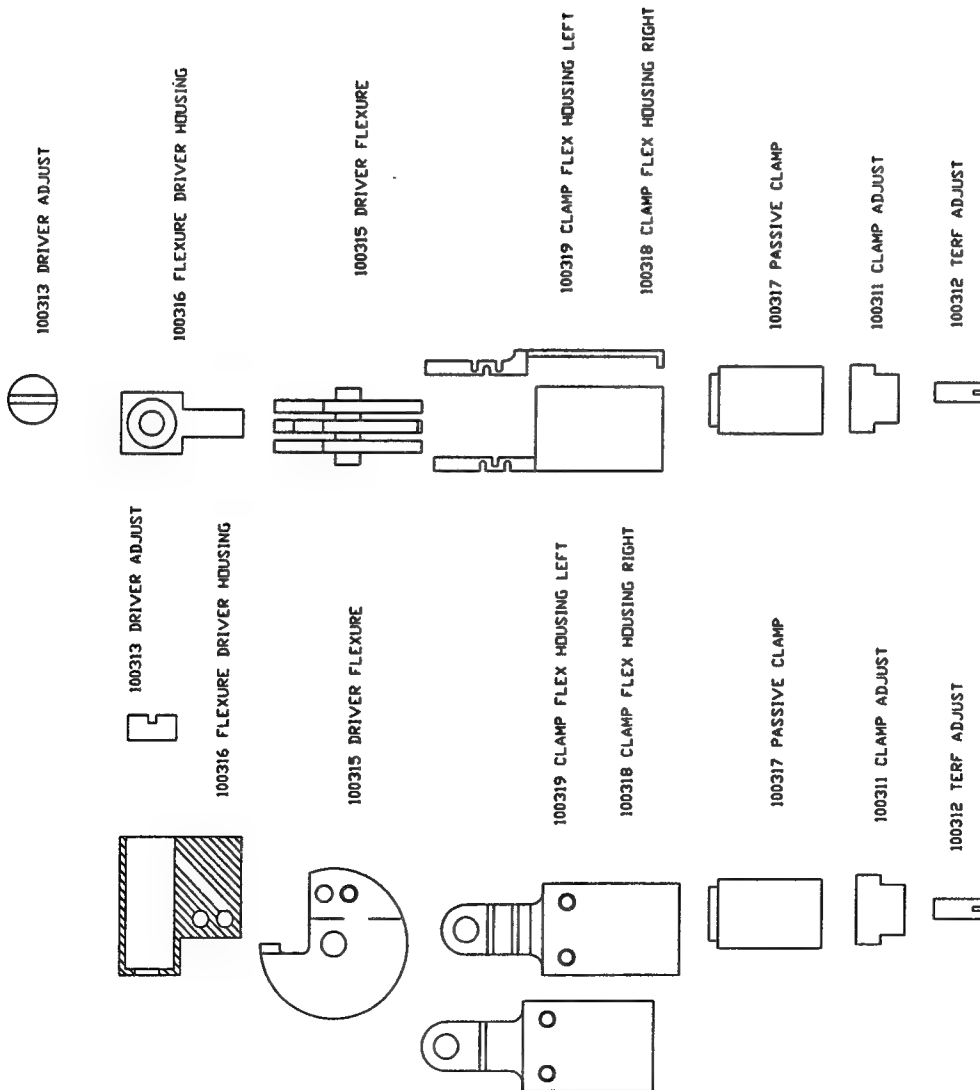
Unless otherwise specified  
 Dimensions are in inches  
 Tolerances on angles ± 0° 30'  
 Fits are in accordance with ASME Y14.5-1994



0.083 DIA THRU  
2 PLACES

tra

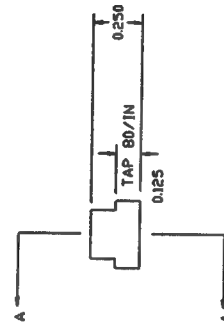
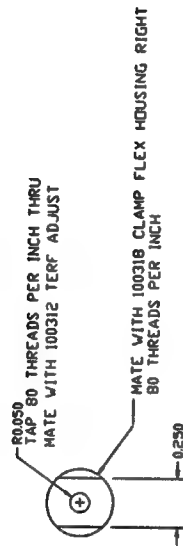
TITLE: CLAMP FLEX HOUSING LEFT		DATE: 3/30/94	NO: 100319
SCALE: 1:1	DATE: 3/30/94	NO: 100319	RELEASE DATE:
DESIGN BY: GOODWIN	DATE: 3/30/94	NO: 100319	XXX
PROJECT ACTUATOR II	DATE: 3/30/94	NO: 100319	APPROVAL:
FILE NAME: 100319.DWG	DATE: 3/30/94	NO: 100319	



trc

TITLE: FLEXURE ACTUATOR ASSEMBLY	
SCALE: 1:1	DATE: 4/8/94
DRAWN BY: GOODWIN	REV: 100320
PROJECT ACTUATOR II	RELEASE DATE:
FILE NAME: 100320.DWG	APPROVAL:

Unless otherwise specified  
 Dimensions are in inches  
 Tolerances on angles ± 0.30°  
 Decimals XX ± 0.01, XXX ± 0.005

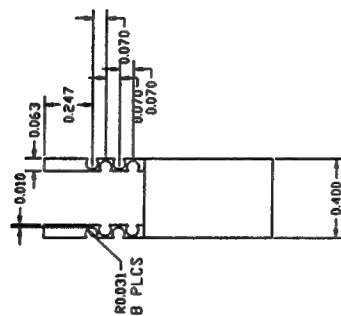
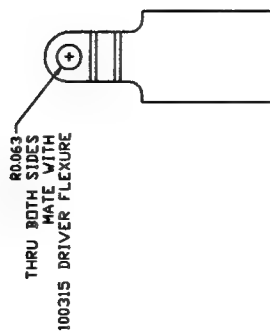
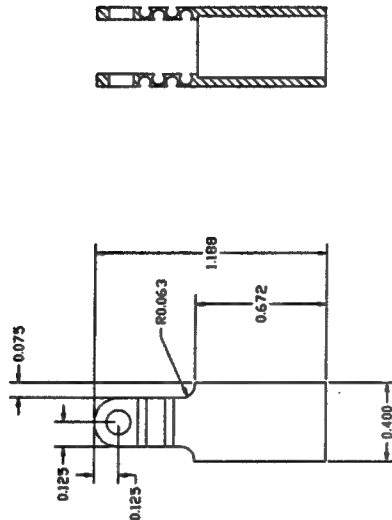


SECTION A-A

tra

TITLE: FLEXURE CLAMP ADJUST			
SCALE: 1:1	DATE: 3/31/94	No. 100321	
DRAWN BY: GOODWIN		RELEASE DATE:	
PROJECT ACTUATOR II		XX	
FILE NAME: 10031.DWG		APPROVAL:	

Notes otherwise specified:  
 Dimensions are in inches unless otherwise noted.  
 Tolerances on angles ± 0.3°  
 Decimals .XX ± 0.2 .XXX ± 0.05

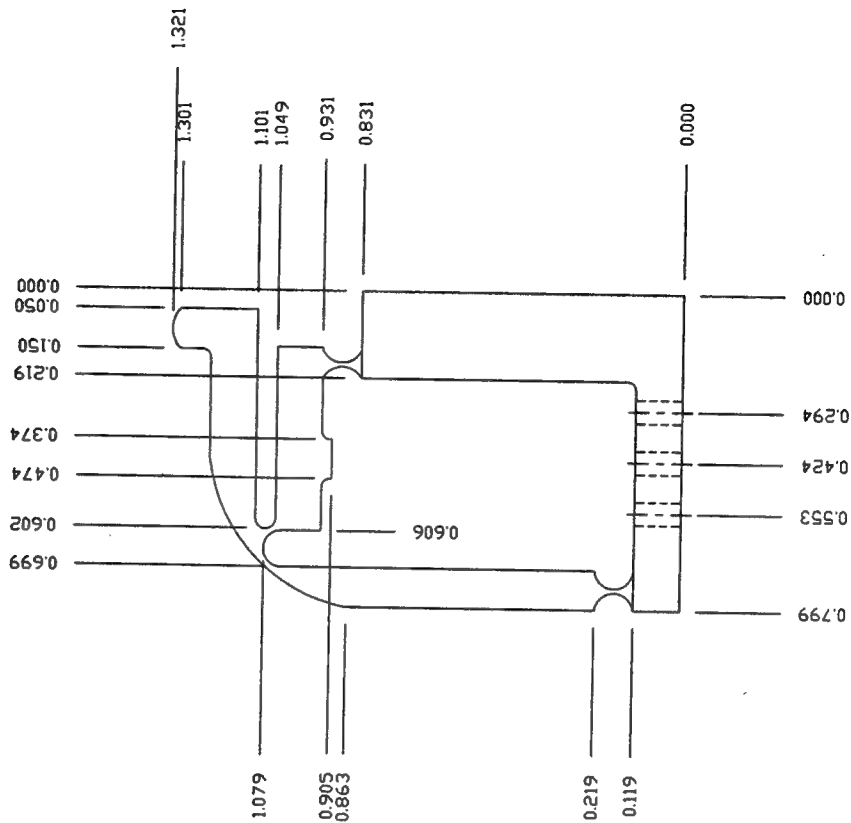
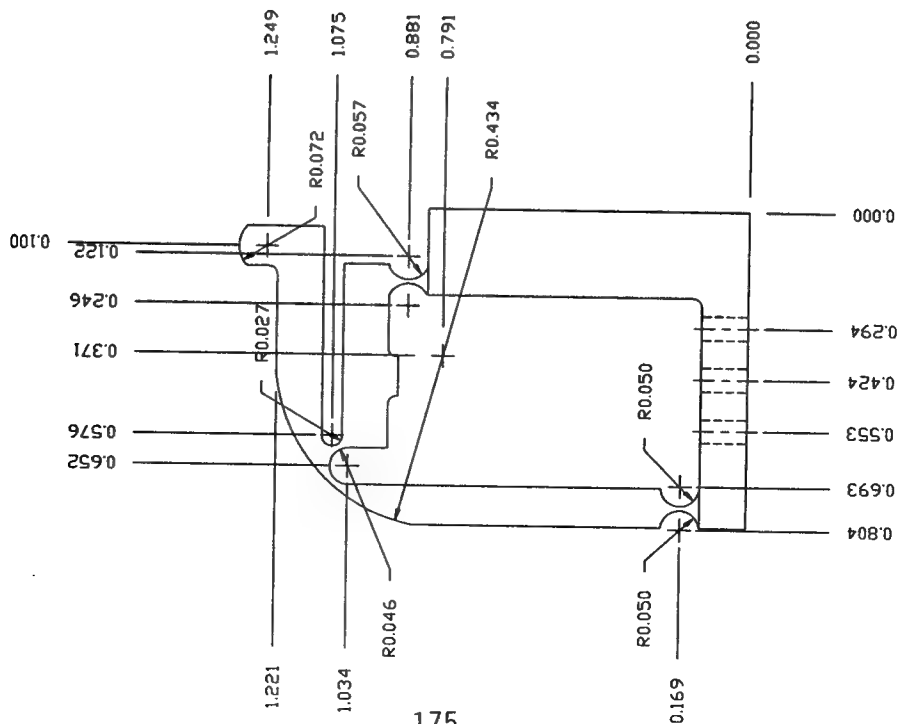


R0.155  
TAP 80 THRDS/IN  
0.200 DP  
MATE WITH 100311 CLAMP ADJUST

tra

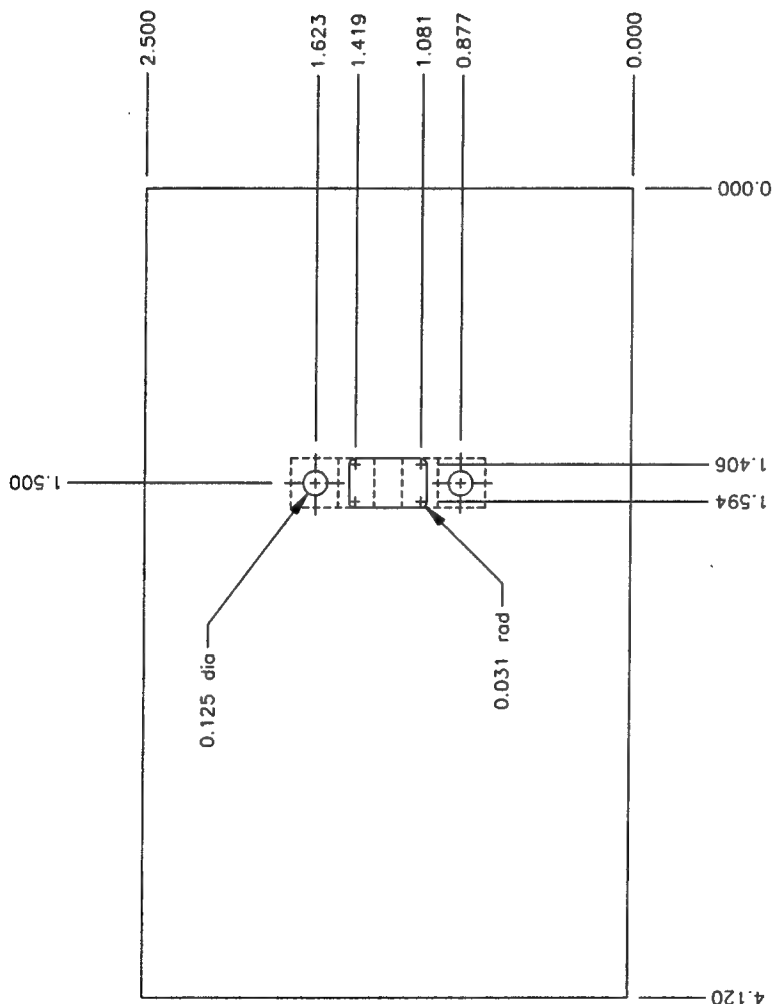
TITLE: CLAMP FLEX HOUSING	
SCALE: 1:1	DATE: 4/21/94
DRAWN BY: GOODWIN	NO: 100323
PROJECT: ACTUATOR II	RELEASE DATE: XIX
FILE NAME: 100323.DWG	APPROVAL:

Unless otherwise specified  
Dimensions are in inches  
Tolerances on angles ± 0° 30'  
Decimals: XX ± .XX, XIX ± .010



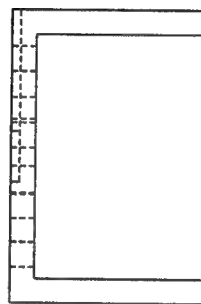
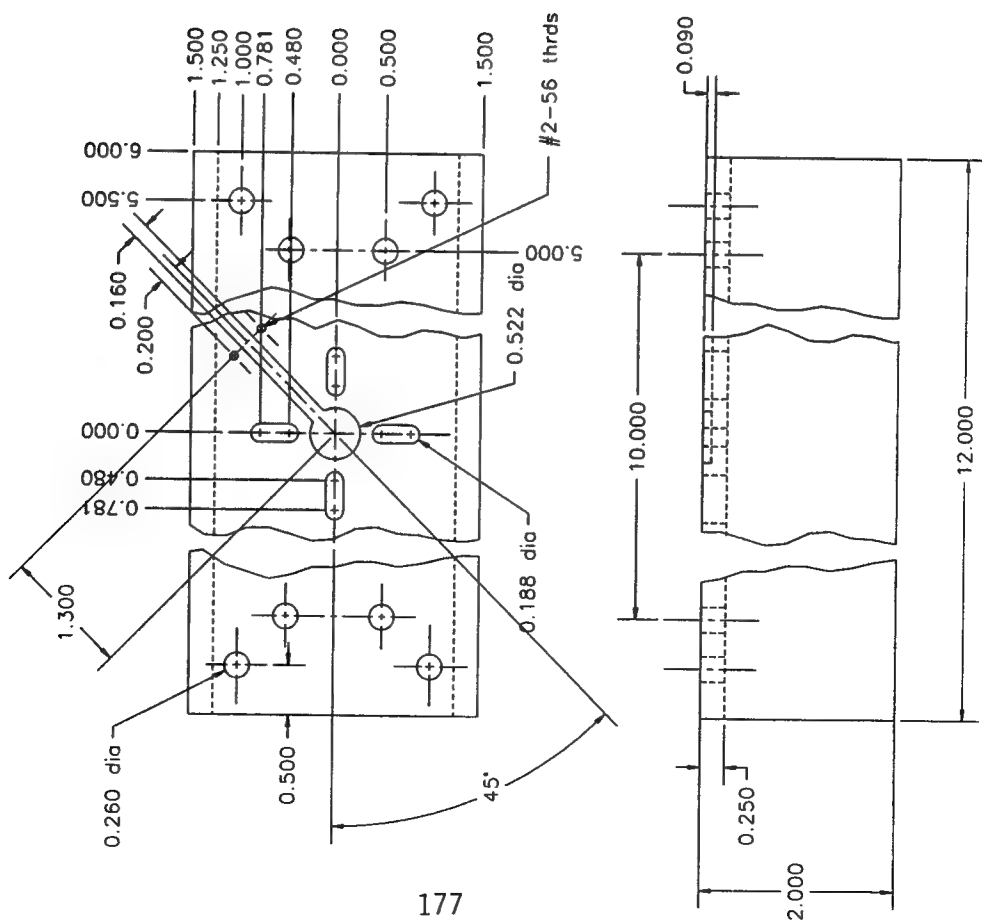
tre

Title: Detail - Deflection Magnifier		DATE: 9 May 94	Rev: BE00127
Scale: 2:1		DATE: 9 May 94	Rev: BE00127
Drawn By: AP Hilton		Release Date:	XXX
Project: Actuator II		Approval:	XXX
File Name: BE00127.dwg			



tra

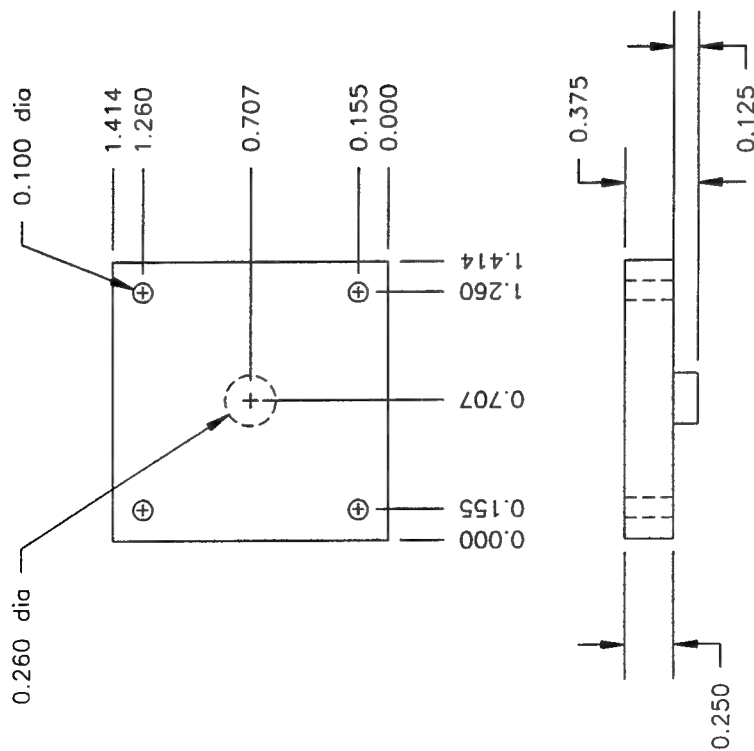
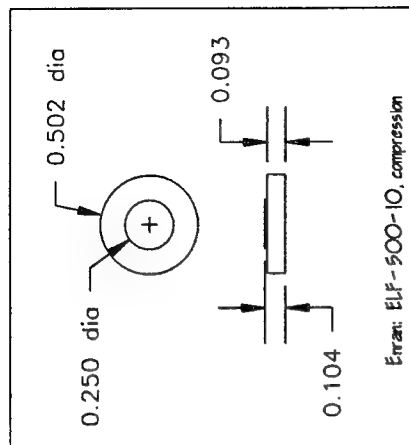
Motion Detector Box Lid			
DATE: 11	DATE: 7 Nov 94	DATE: BE00163	DATE: XXX
REV: A	REV: A	REV: A	REV: A
DESIGN: AUM	DESIGN: A. P. Hilton	DESIGN: A. P. Hilton	DESIGN: A. P. Hilton
PROJECT: Actuator II	PROJECT: Actuator II	PROJECT: Actuator II	PROJECT: Actuator II
TEST: Test	TEST: Test	TEST: Test	TEST: Test
TIL MMU BE00163.dwg			



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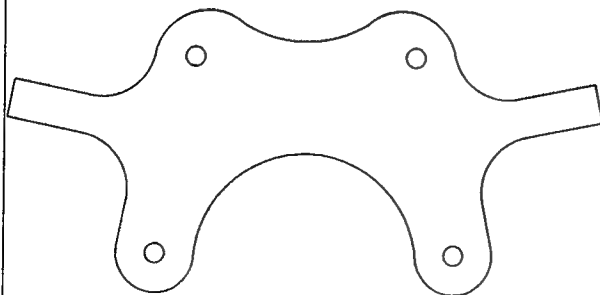
REV B	Load Cell Calibration Bed			
	TITLE	1:2	DATE: 29 Dec 94	No: BE00177
	SCALE		RELEASE DATE:	
	DRAWN BY: A. P. Hilton		XXX	
Unless otherwise specified Dimensions are in inches Tolerances on angles & J Dimensions .005, .010, .015, .020, .030, .040, .050, .060, .070, .080, .090, .100, .125, .150, .175, .200, .250, .300, .375, .500, .625, .750, .875, 1.000, 1.250, 1.500, 1.750, 2.000, 2.500, 3.000, 3.500, 4.000, 4.500, 5.000, 5.500, 6.000, 6.500, 7.000, 7.500, 8.000, 8.500, 9.000, 9.500, 10.000, 10.500, 11.000, 11.500, 12.000, 12.500, 13.000, 13.500, 14.000, 14.500, 15.000, 15.500, 16.000, 16.500, 17.000, 17.500, 18.000, 18.500, 19.000, 19.500, 20.000, 20.500, 21.000, 21.500, 22.000, 22.500, 23.000, 23.500, 24.000, 24.500, 25.000, 25.500, 26.000, 26.500, 27.000, 27.500, 28.000, 28.500, 29.000, 29.500, 30.000, 30.500, 31.000, 31.500, 32.000, 32.500, 33.000, 33.500, 34.000, 34.500, 35.000, 35.500, 36.000, 36.500, 37.000, 37.500, 38.000, 38.500, 39.000, 39.500, 40.000, 40.500, 41.000, 41.500, 42.000, 42.500, 43.000, 43.500, 44.000, 44.500, 45.000, 45.500, 46.000, 46.500, 47.000, 47.500, 48.000, 48.500, 49.000, 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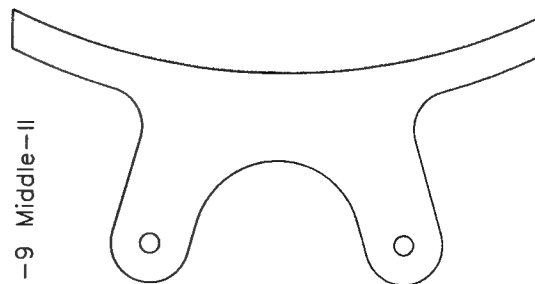


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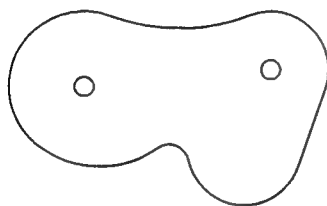
TITLE: Calibration Bed Load Positioner		SCALE: 1:1	DATE: 28 Dec 94	NO: BE00178
REV A		DESIGN BY: A. P. Hilton	RELEASE DATE: XXX	
PROJECT: Actuator II		FILE NAME: be00178.dwg	APPROVAL:	
UNLESS OTHERWISE SPECIFIED		TOLERANCES ARE IN INCHES		
DIMENSIONS ON ANGLES < 90°		TOLERANCES ARE IN INCHES		
DECIMALS .XX ± .01		TOLERANCES ARE IN INCHES		
FRACTIONS 1/16 ± .005		TOLERANCES ARE IN INCHES		



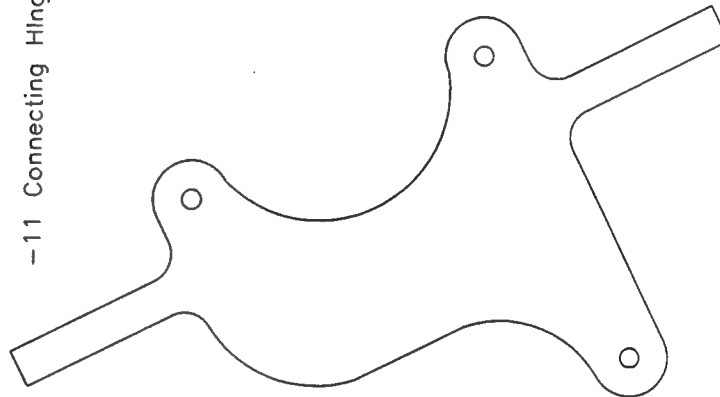
-3 Distal-II



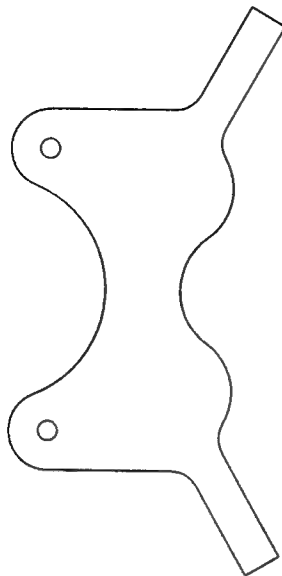
-9 Middle-II



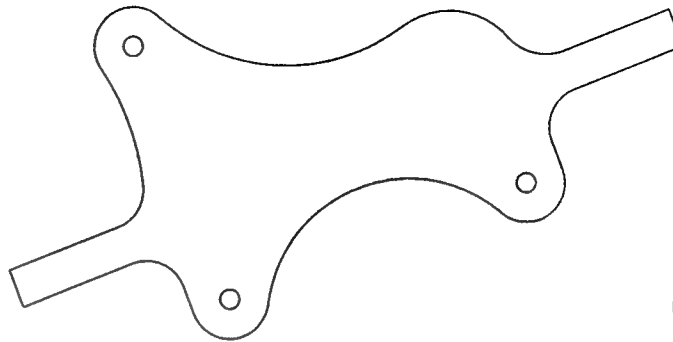
-11 Connecting Hinge-II



-5 Proximal-II



-13 Distal-I

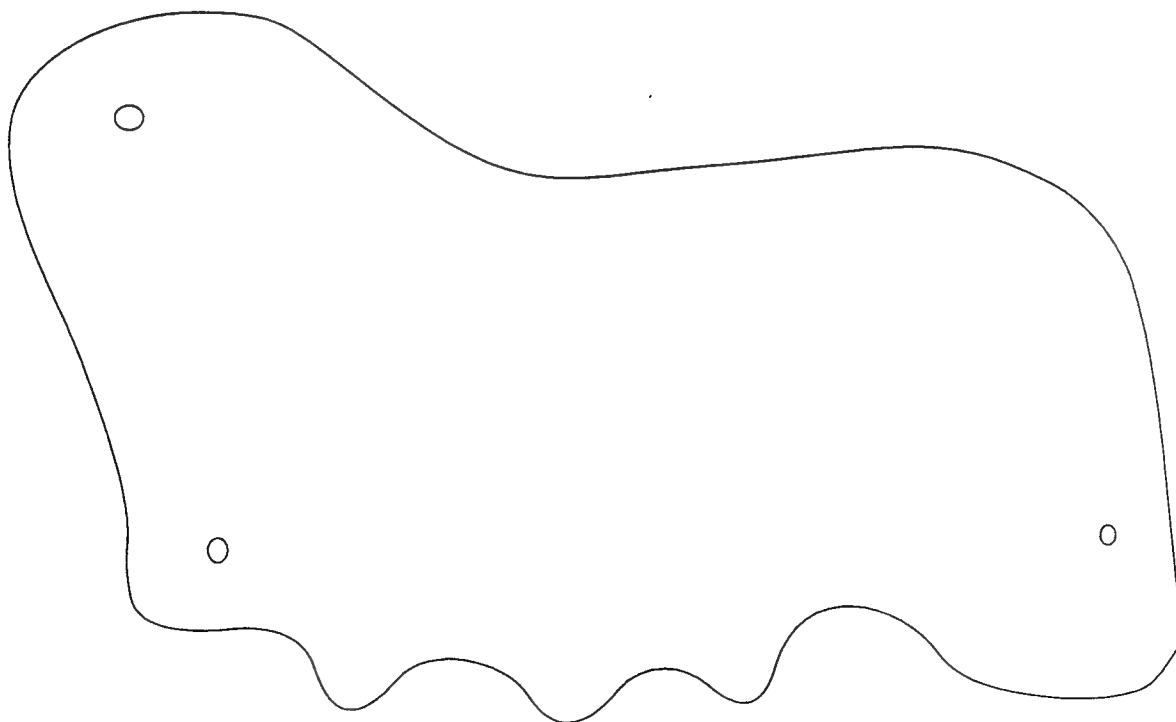


-7 Middle-I

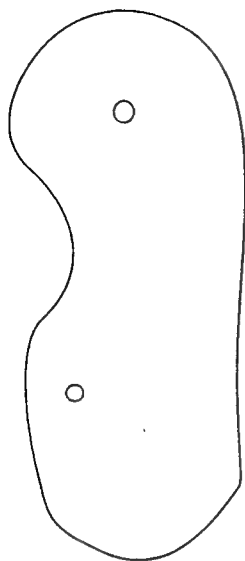
179

Exoskeleton -1

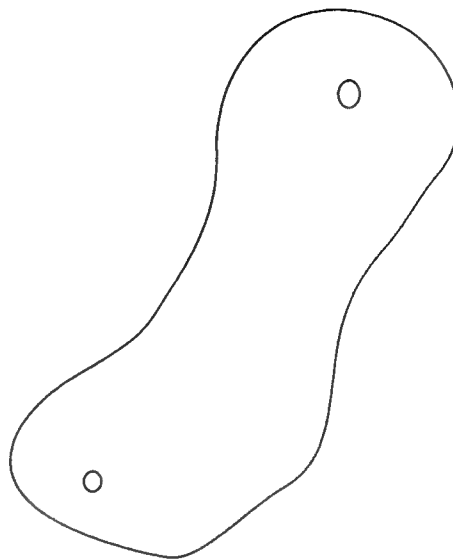
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES ON ANGLES ± 0° 30' DECIMALS XX ± .02, XXX ± .005	REV A	DATE 22 Feb 95	Mr. BE000193
DESIGNED BY: A. P. Hilton	PROJECT ACTUATOR II	RELEASE DATE:	XXX
FILE NAME: 0601032949	APPROVAL:		



-3 Hand



-5 Connecting Hinge-1

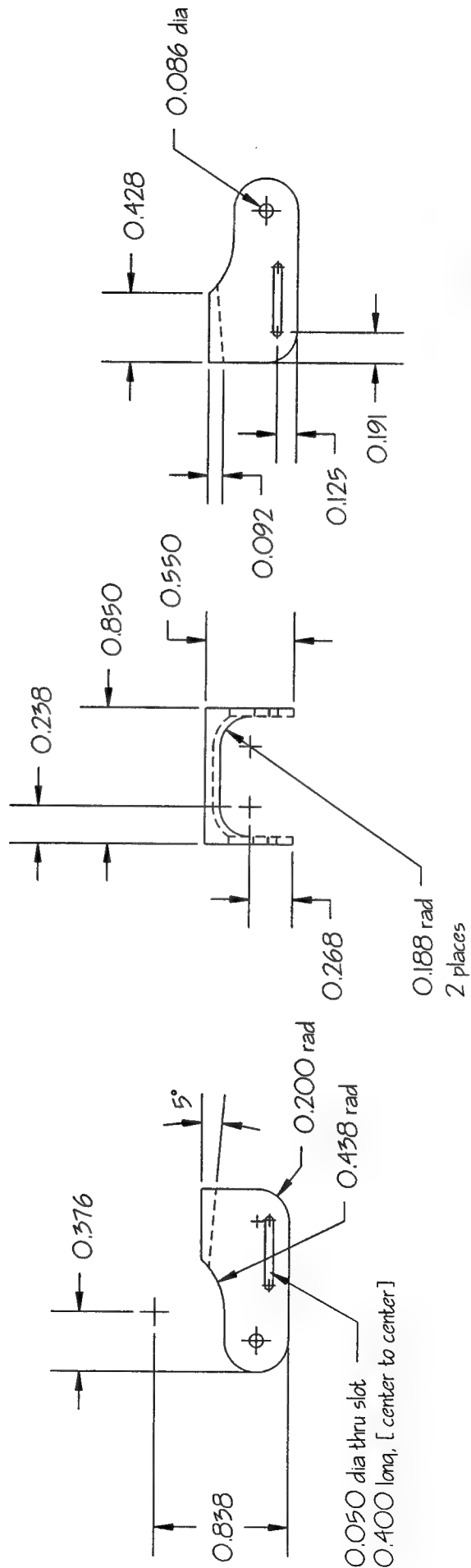
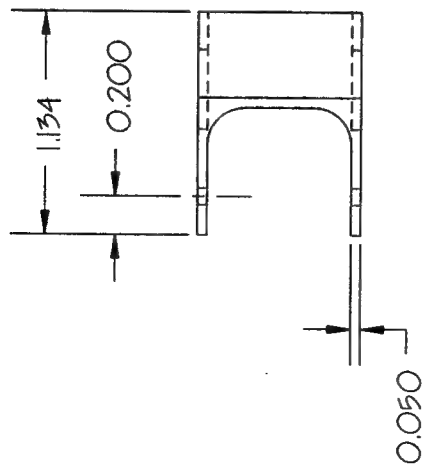


-7 Digit 1, Proximal

tree

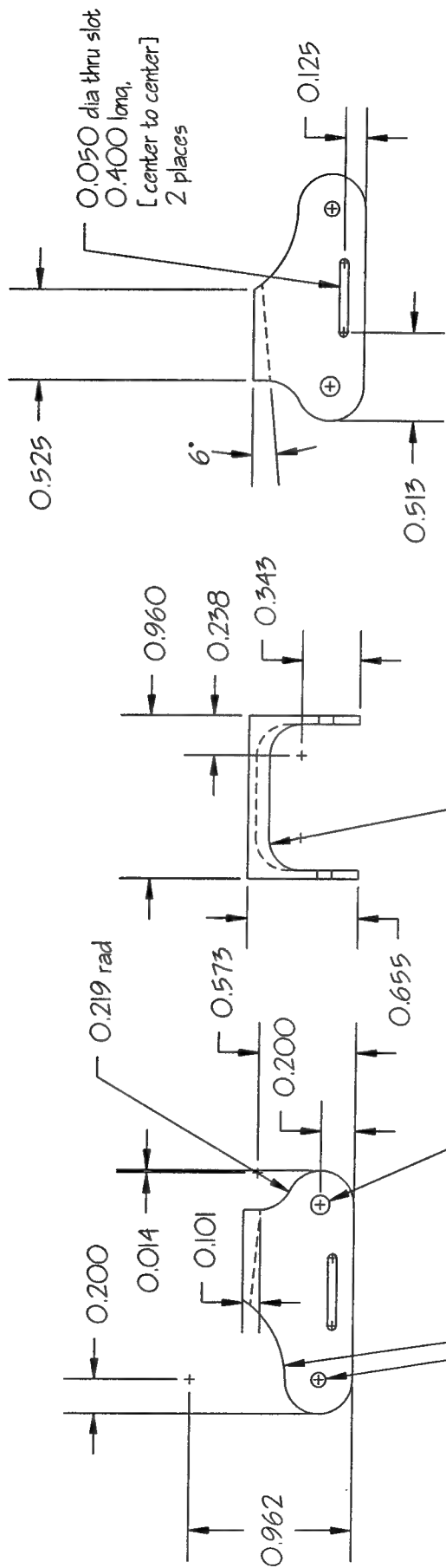
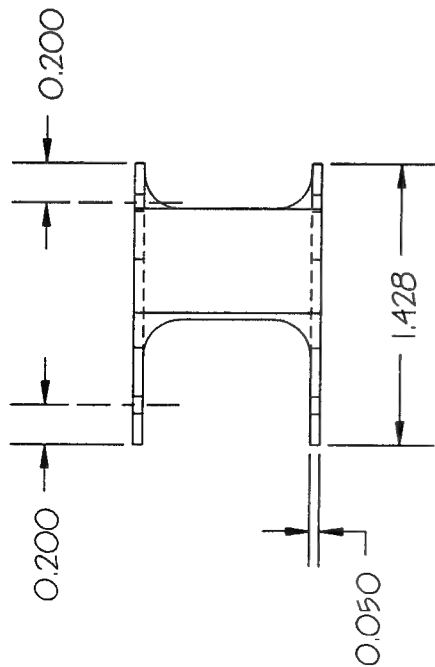
FILE: Exoskeleton -2

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES UNLESS OTHERWISE SPECIFIED: DECIMALS .XX ± .005 FRACTIONS 1/16 ± .005	REV B	DATE: 1 Mar 95	NO. BE000194
DESIGNED BY: A. P. Hilton	PROJECT: Actuator II	RELEASE DATE: 1 Mar 95	APPROVAL
CHECKED BY: No	FILE NAME: be000194.dwg		



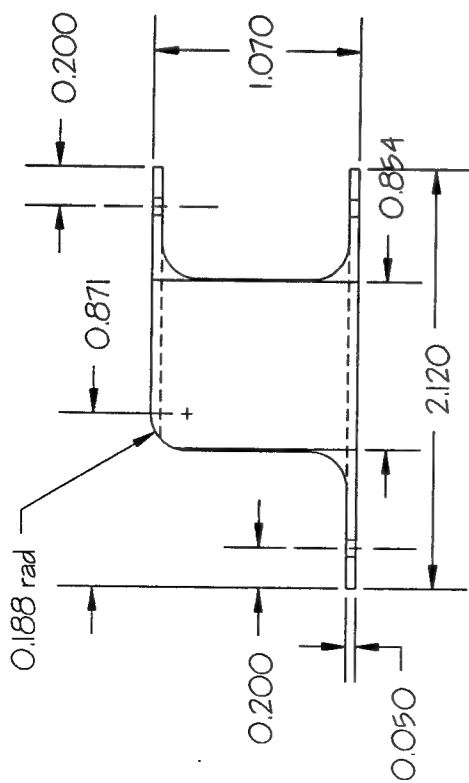
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TITLE: Digit 2, Distal		DATE: 27 Feb 95	NO: BE000196
SCALE: 1:1	DESIGN BY: A. P. Hilton	PROJECT: Estimator II	RELEASE DATE: 10 Mar 95
REV: B	FILE NAME: BE000196.dwg	APPROVAL:	
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON ANGLES: 0°-30° MACH. ALIAS DECIMALS .XX ± .02 .XXX ± .005			

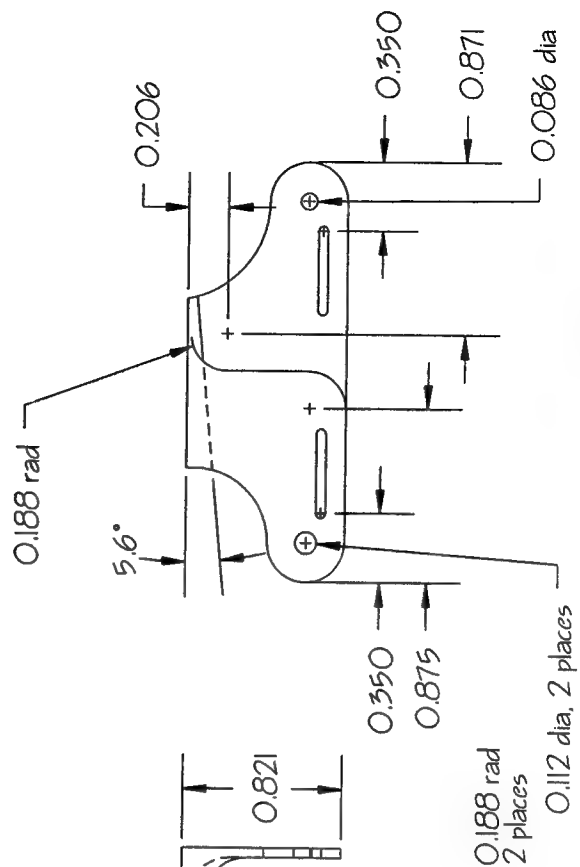
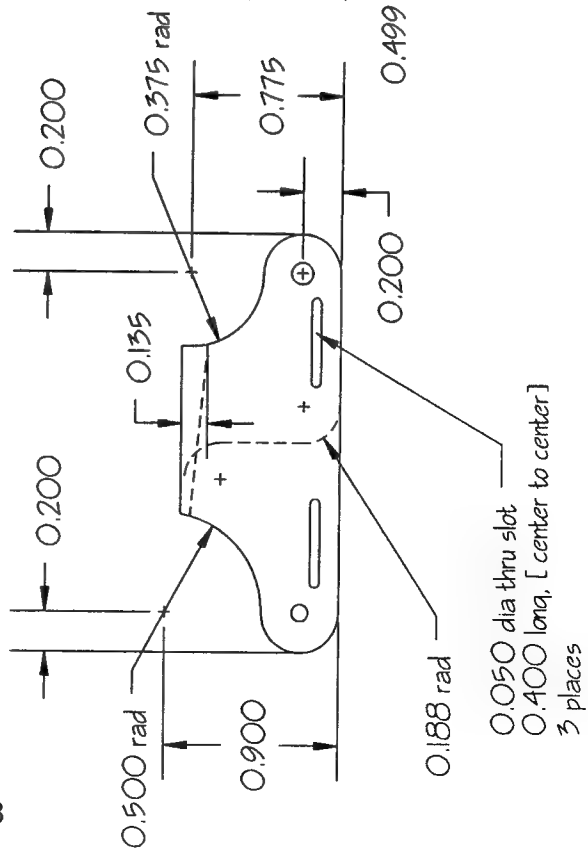


trc

Drawn by: A. P. Hilton	DATE: 27 Feb 95	REV: B	FILE NAME: trc0197.dwg
Project: Actuator II	Scale: 1:1	Part: 1 of 1	Part: 1 of 1
Release Date: 10 Mar 95	Part: 1 of 1	Part: 1 of 1	Part: 1 of 1
Approval:	Part: 1 of 1	Part: 1 of 1	Part: 1 of 1



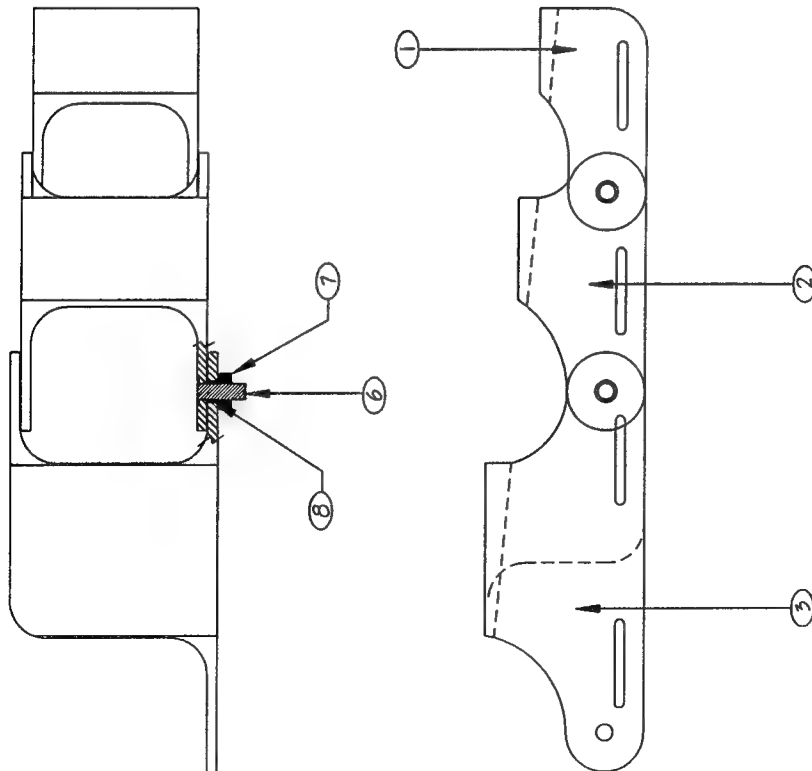
183



trc

mil. Digit 2, Proximal

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON ANGLES ± 0° 30' DECIMALS XX ± 0.02, XXX ± 0.005	SCALE 1:1	DATE 27 Feb 95	W. BEC000198
REV B	DESIGNER A. P. Hilton	RELEASE DATE: 10 Mar 95	
PROJECT ACTUATOR II	FILE NAME BEC00198.dwg	APPROVAL	



- ③ Small Parts, Miami Lakes, FL 305-557-8222
- ② Fasteners of Comparable Spec's Acceptable
- ① Hypodermic Tubing Cut to 0.065" Length

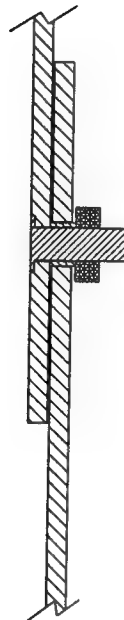
①  
②  
③

5	8	Q-HRX-12	12 Gauge - Hypodermic Tubing	304W/SS
5	7	Q-HRX-256	#2-56 Hex Nut	SS
5	6	Q-55X-256-4	#2-56 x 1/4" Self Clenching Stud	-- SS
1	5	XXX	XXX	--
1	4	XXX	XXX	--
1	3	PE000198	Dist 2 Proximal	--
1	2	PE000197	Dist 2 Middle	--
1	1	PE000196	Dist 2 Distal	--
---	---	PE000199	Dist 2 - ASSEMBLY	--
QTY	ITEM	PART NO.	DESCRIPTION	MAT'L / SPEC
REQD	NO.			

# PARTS LIST

tra

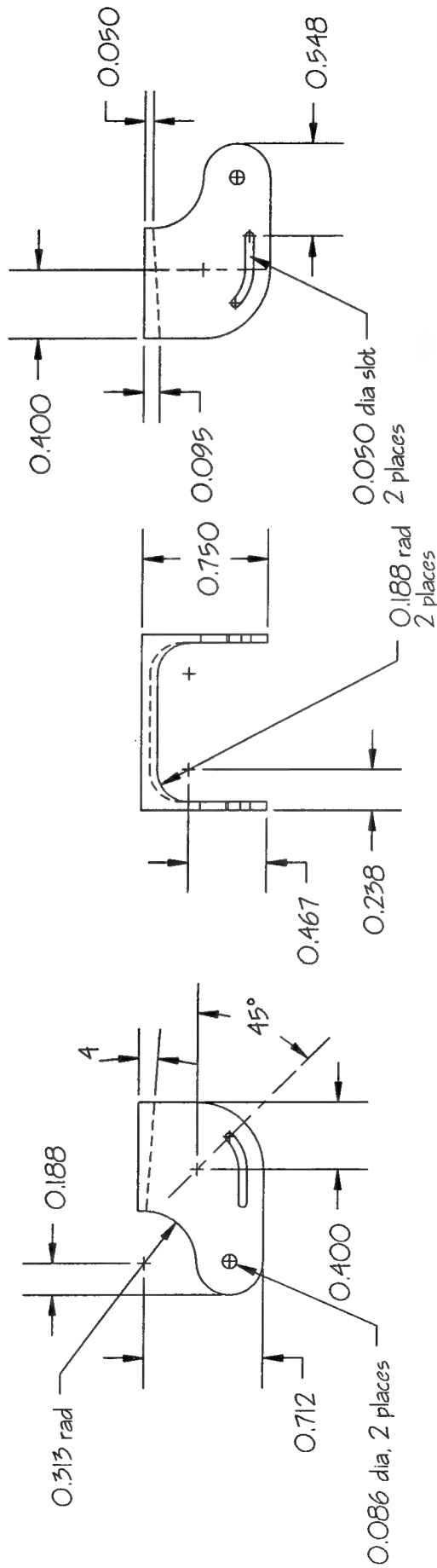
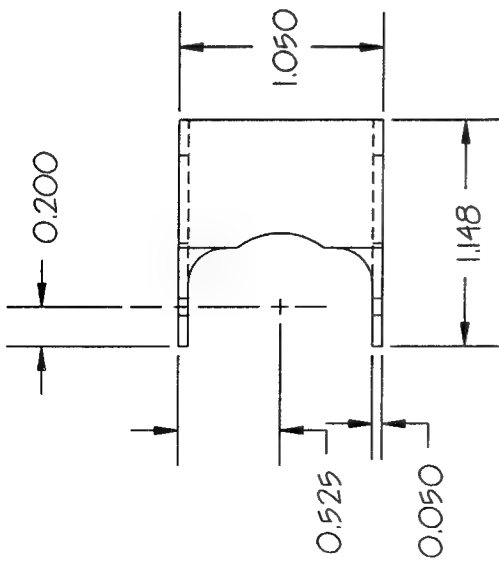
Title: Assembly - Digit 2	
Scale: 1:1	Date: 28 Feb 95
Drawn By: A. P. Hilton	Release Date: 10 Mar 95
Project: Actuator II	Approval:
Part: XXX	Part: XXX
Rev: B	Rev: B
Unless otherwise specified, dimensions are in inches ± .01	Material: XXX ± .005
Decimals: XX ± .01, XXX ± .005	Heat Treat: No



tr

TITLE: Connector Detail		SCALE: 2:1		DATE: 28 Feb 95		No. BE000200	
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES FRACTIONS ARE 16ths OF AN INCH DECIMALS ARE TO 3 DECIMALS		REV A		DRAWN BY: A. P. Hilton		RELEANT DATE: XXX	
				PROJECT ACTUATOR II		APPROVAL	
				FILE NAME: be000200.dwg			

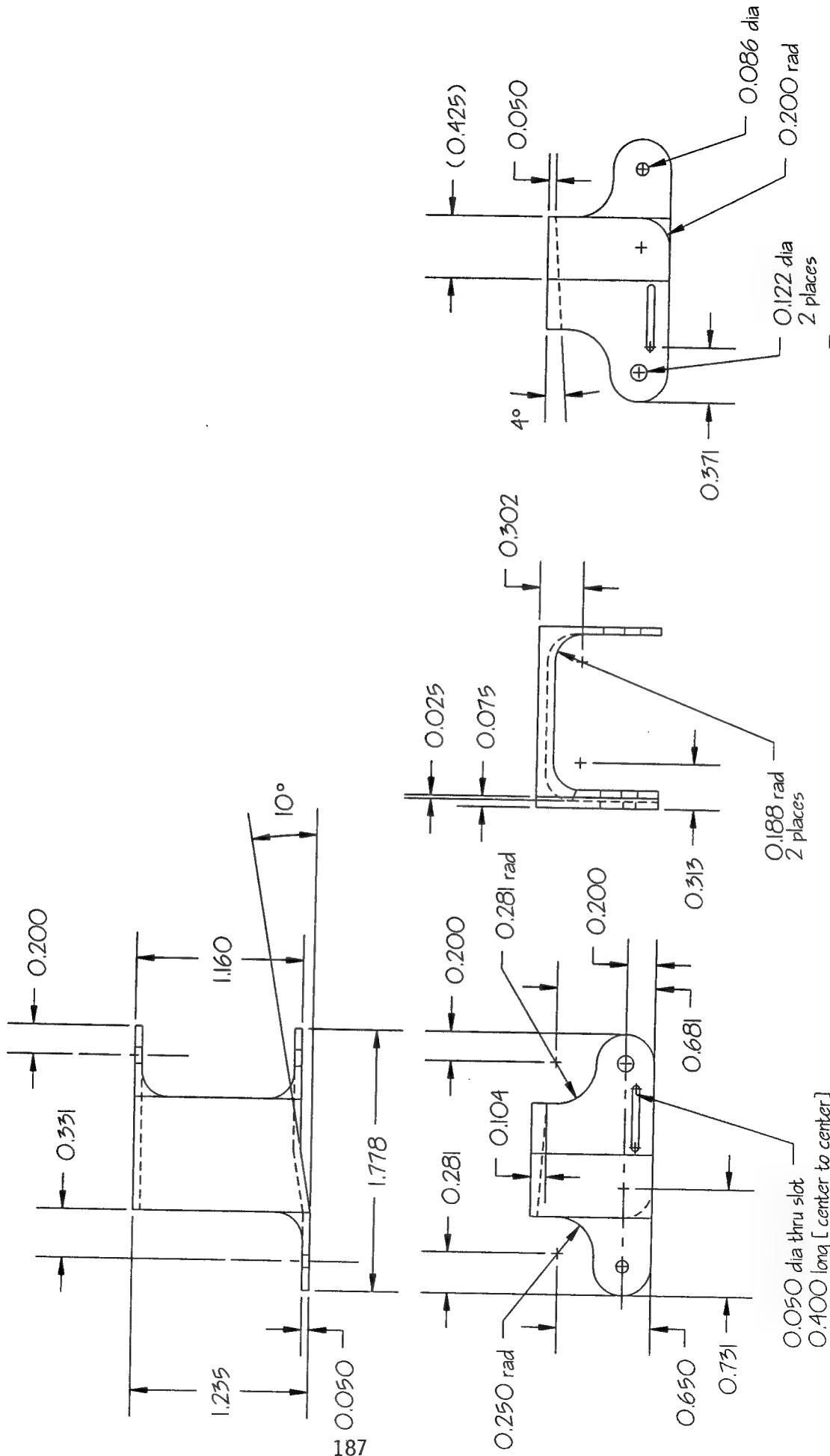




trc

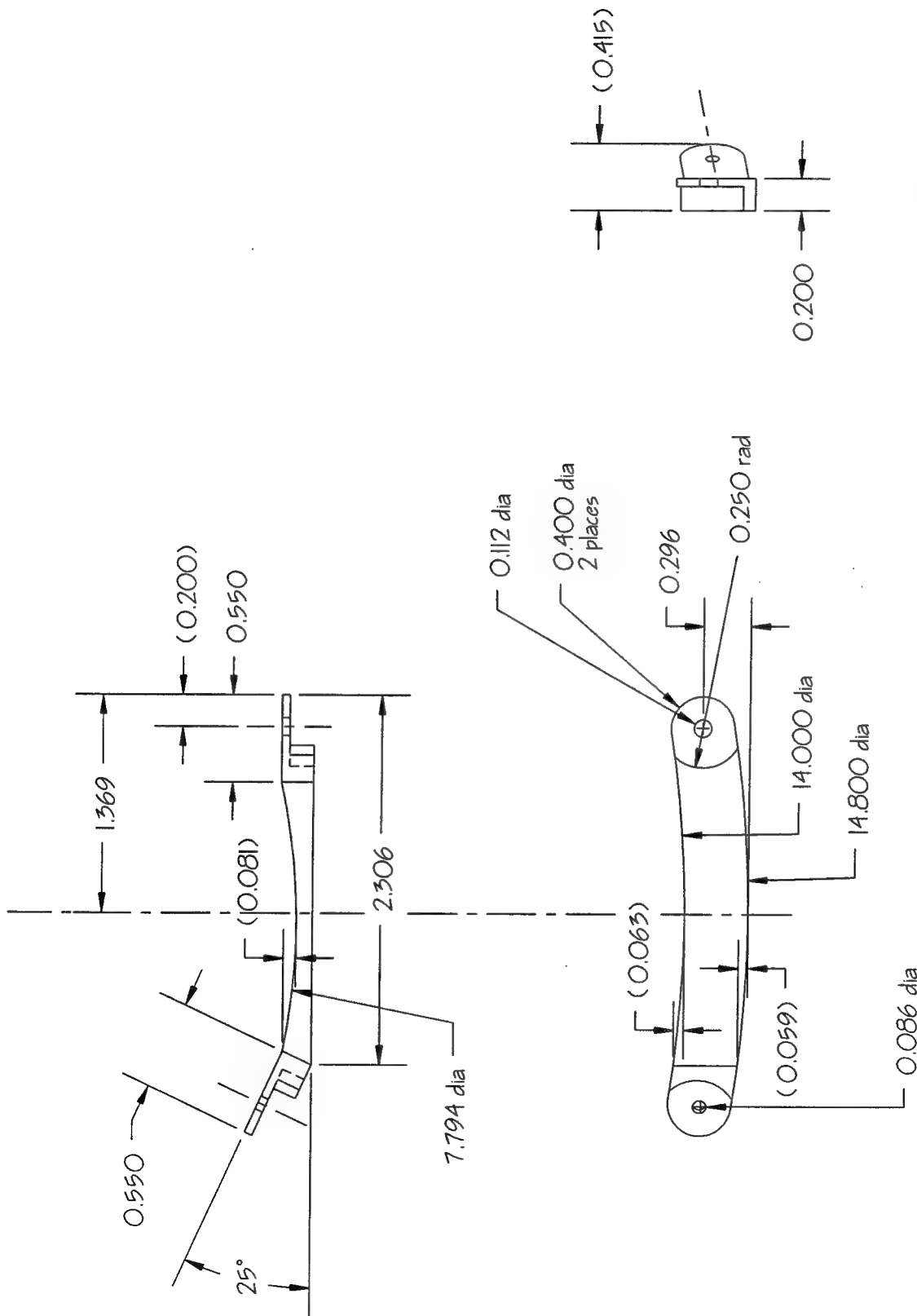
Doc. Digit 1 - Distal

DESIGN APPROVED	REV B	DATE: Mar 95	No. BE000201
DESIGNED BY	REV B	DATE: Mar 95	RELEASE DATE:
Checked by	REV B	DATE: Mar 95	10 Mar 95
Tolerances on angles ± 0° 30'	REV B	DATE: Mar 95	APPROVAL
Decimals .XX ± 0.01 .XXX ± 0.005	REV B	DATE: Mar 95	
FILE NAME: 0000000000	REV B	DATE: Mar 95	



tree

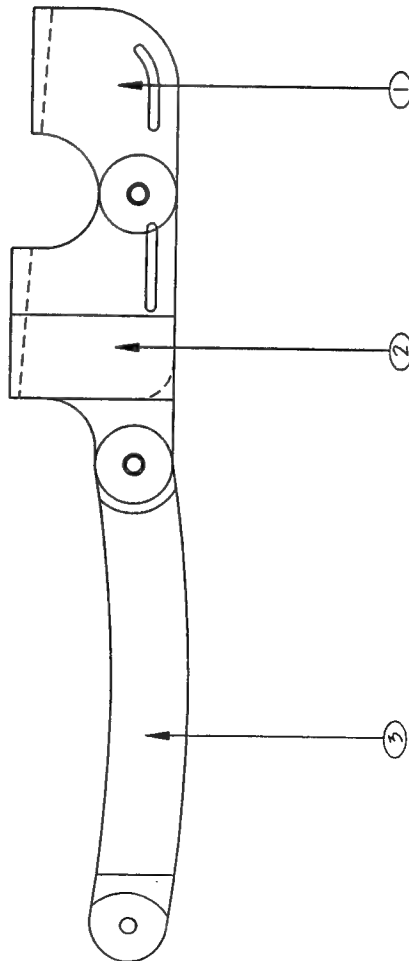
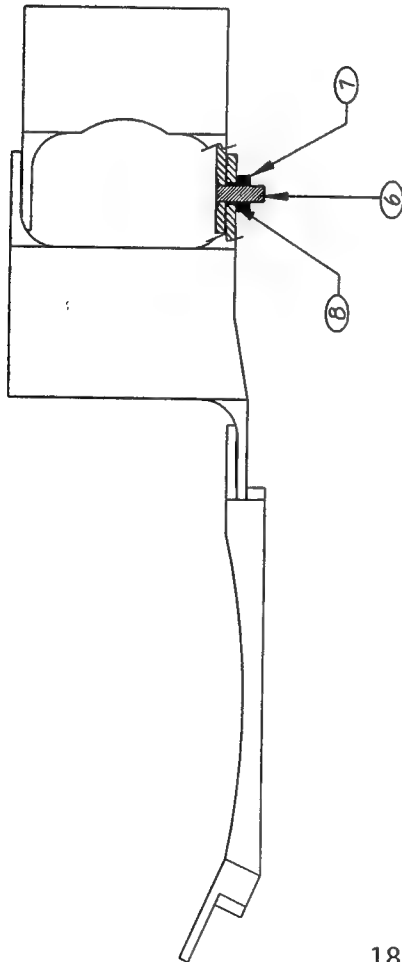
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES ON DIMENSIONS: DECIMALS .XX ± .01 .XXX ± .005	REV B	DATE: 1 Mar 95	FILE NAME: b0000202.dwg
DESIGN BY: A. P. Hilton	REV B	DATE: 1 Mar 95	FILE NAME: b0000202.dwg
PROJECT: Actuator II	REV B	DATE: 1 Mar 95	FILE NAME: b0000202.dwg
APPROVAL:	REV B	DATE: 1 Mar 95	FILE NAME: b0000202.dwg



tr

REV B

DATE: 11	DATE: 3 Mar 95	NO. BE000203
DESIGNER: A. P. Hilton	RELEASE DATE: 10 Mar 95	
PROJECT: Actuator II	APPROVAL:	
FILE NAME: act0203.dwg		



- ③ Small Parts, Miami Lakes, FL 305-557-8222
- ② Fasteners of Comparable Spec's Acceptable
- ① Hypodermic Tubing Cut to 0.065" Length

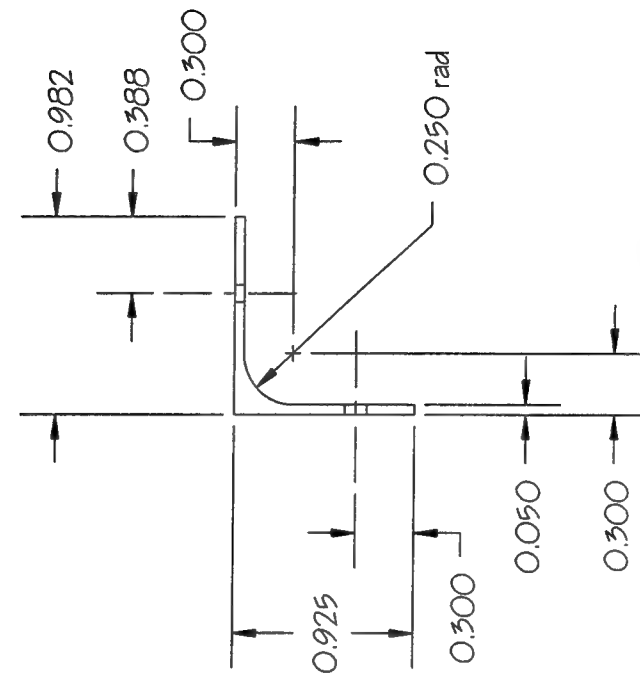
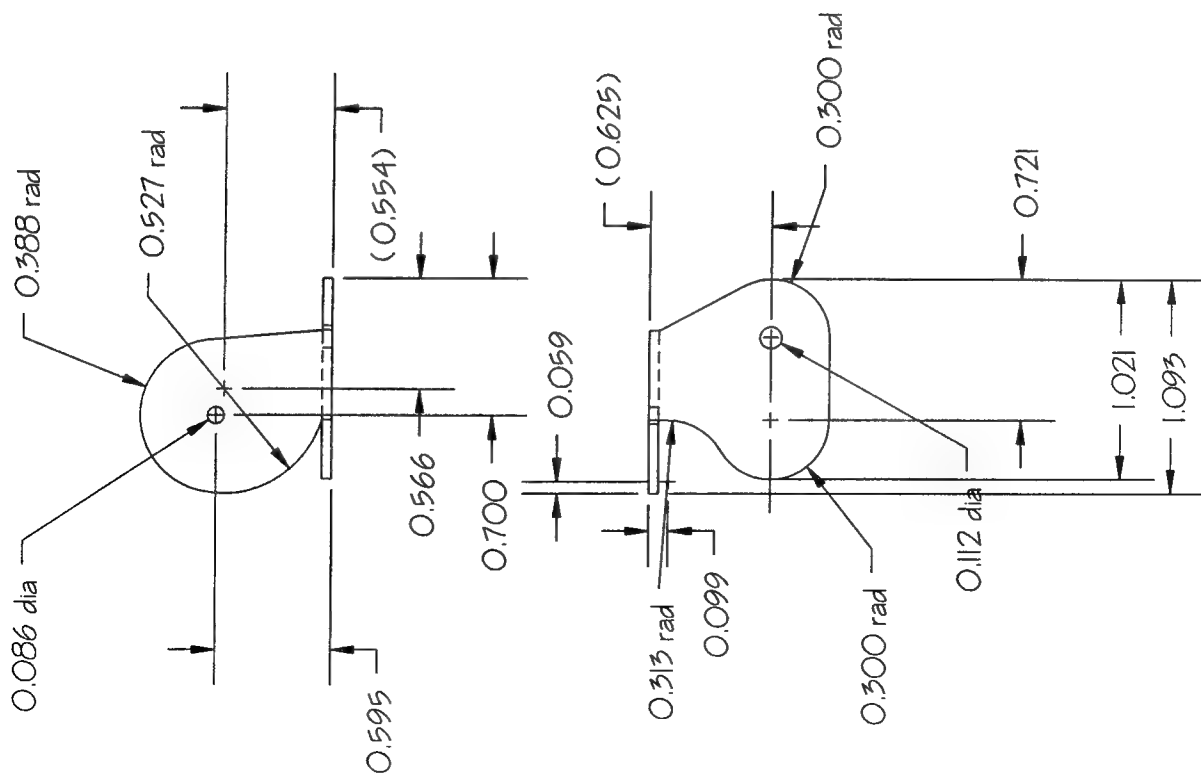
①  
②  
③

5	8	Q-MK-12	12 Gauge - Hypodermic Tubing	30AW 55
5	7	Q-MK-256	#2-56 Hex Nut	55
5	6	Q-55K-256-4	#2-56 x 1/4" Self Clenching Stud - 55	---
1	5	XXX	XXX	---
1	4	XXX	XXX	---
1	3	PE000203	Digit 1, Proximal	---
1	2	PE000202	Digit 1, Middle	---
1	1	PE000201	Digit 1, Distal	---
---	---	PE000204	Digit 1 - ASSEMBLY	---
QTY REQD	ITEM NO.	PART NO.	DESCRIPTION	MAT'L / SPEC

# PARTS LIST

tree

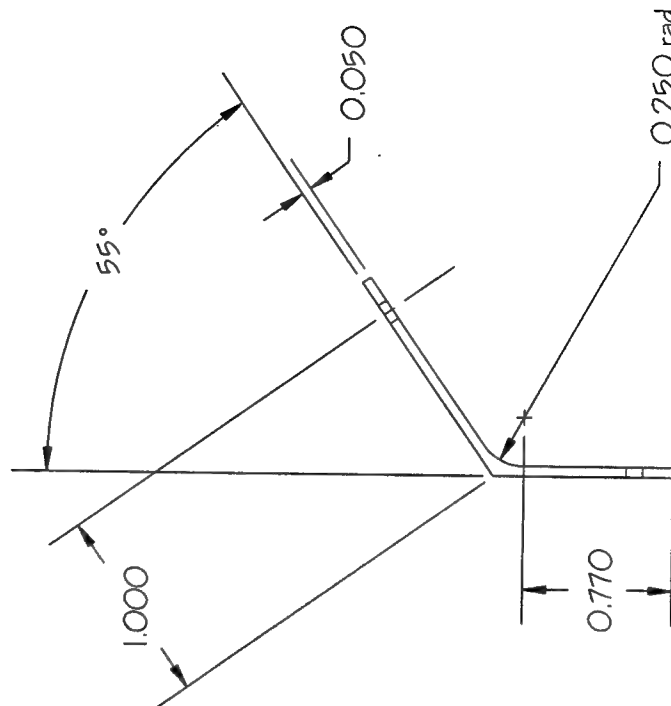
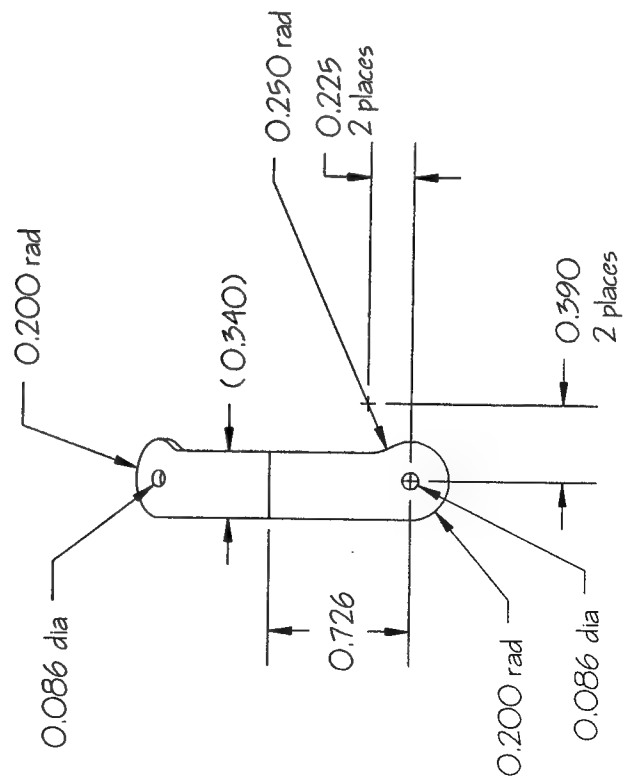
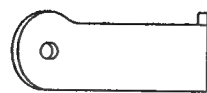
TITLE: Assembly - Digit 2		SCALE: 1:1	DATE: 6 Mar 95	Mr. BE000204
DESIGNER: A. P. Hilton		DRAWN BY: A. P. Hilton		RELEASE DATE: 6 Mar 95
PROJECT ACTUATOR II		FILE NAME: BE000204.dwg		APPROVAL:



tra

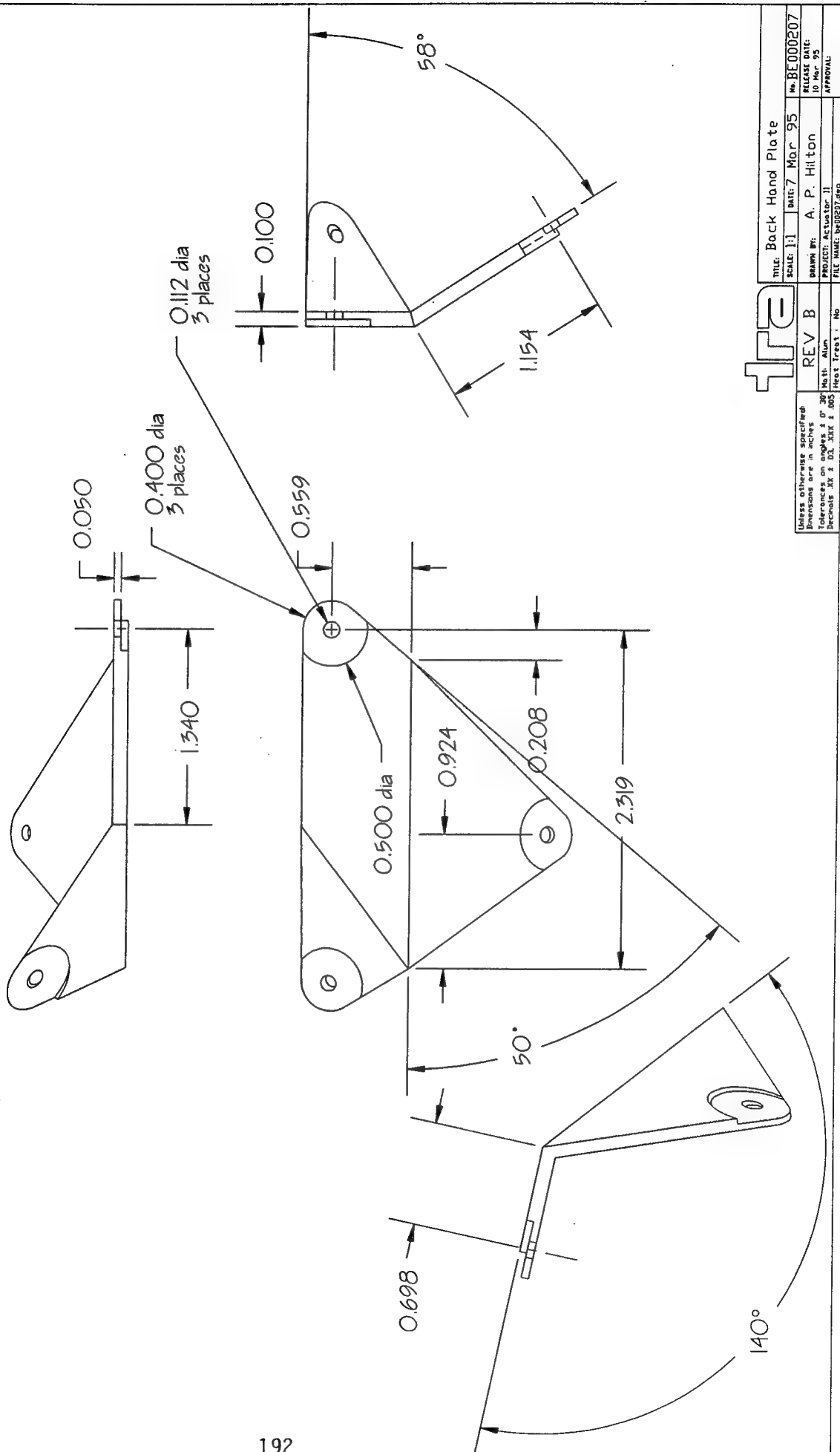
Connecting Hinge - Digit 2			
DATE: 11	DATE: 6 Mar 95	NO: BE000205	RELEASE DATE: 10 Mar 95
REV: B	DESIGN BY: A. P. Hilton	PROJECT: Actuator II	APPROVAL:
FILE NAME: BE000205.dwg			

Unless otherwise specified:  
 Dimensions are in inches  
 Tolerances on angles:  $\pm 0.3^\circ$   
 Tolerances on diameters:  $\pm 0.005$   
 Tolerances on radii:  $\pm 0.005$



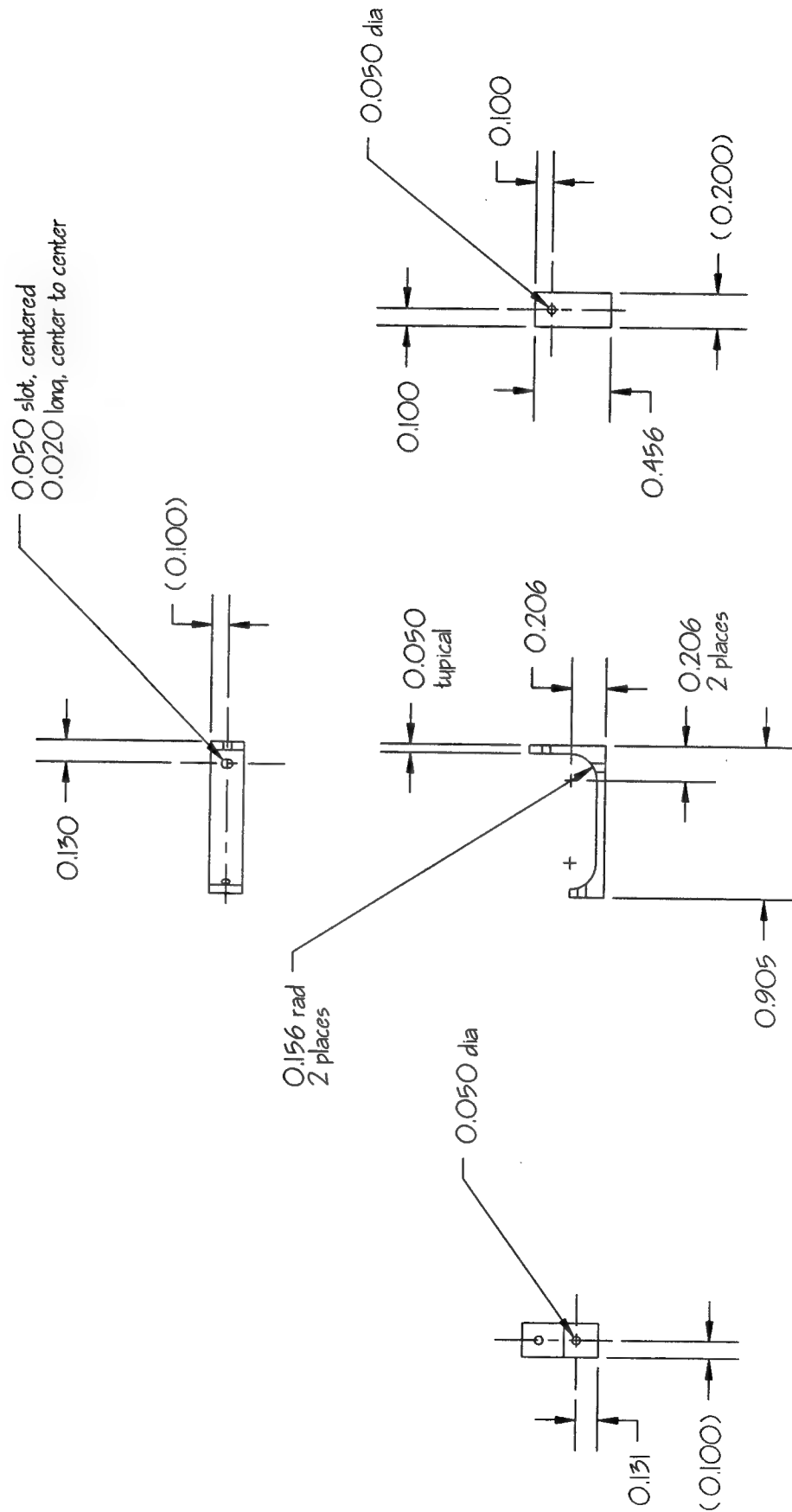
trc

TITLE: Connecting Hinge - Digit 1		SCALE: 1:1	DATE: 6 Mar 95	NO: BE000206
DRAWN BY: A. P. Hilton		REV: B	PROJECT: Actuator II	RELEASE DATE: 10 Mar 95
FILE NAME: BE000206.dwg		West: Alum	West: Treat: No	APPROVAL:



tr2

TITLE: Back Hand Plate			
SCALE: 1:1	DRAWN BY: A. P. Hilton	DATE: 7 Mar 95	NO: BE000207
REV B	PROJECT: Actuator II	RELEASE DATE: 10 Mar 95	APPROVAL:
REV B	PROJECT: Actuator II	FILE NAME: be000207.dwg	

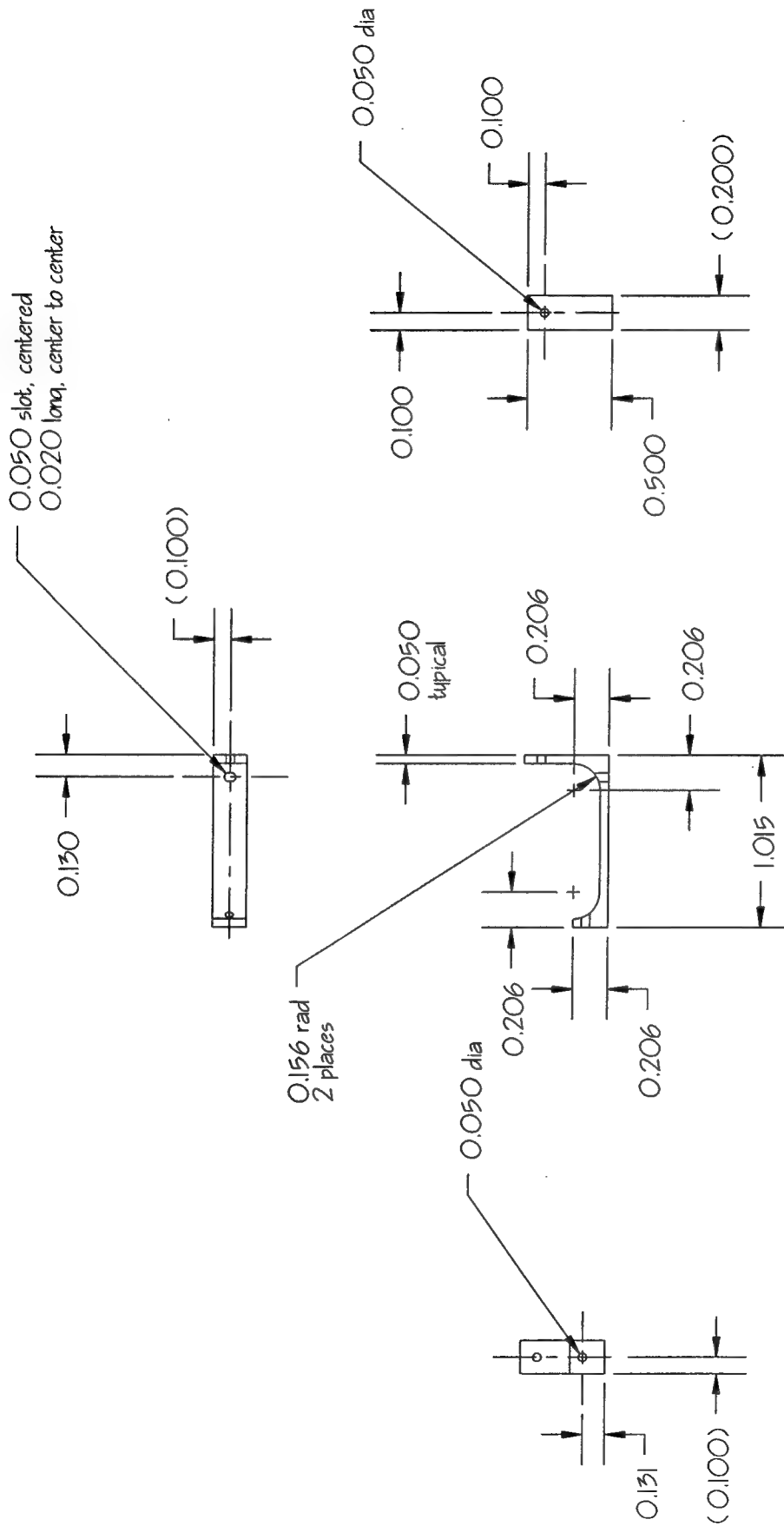


Note: Use 00-90 x 3/16 flat head screws

tree

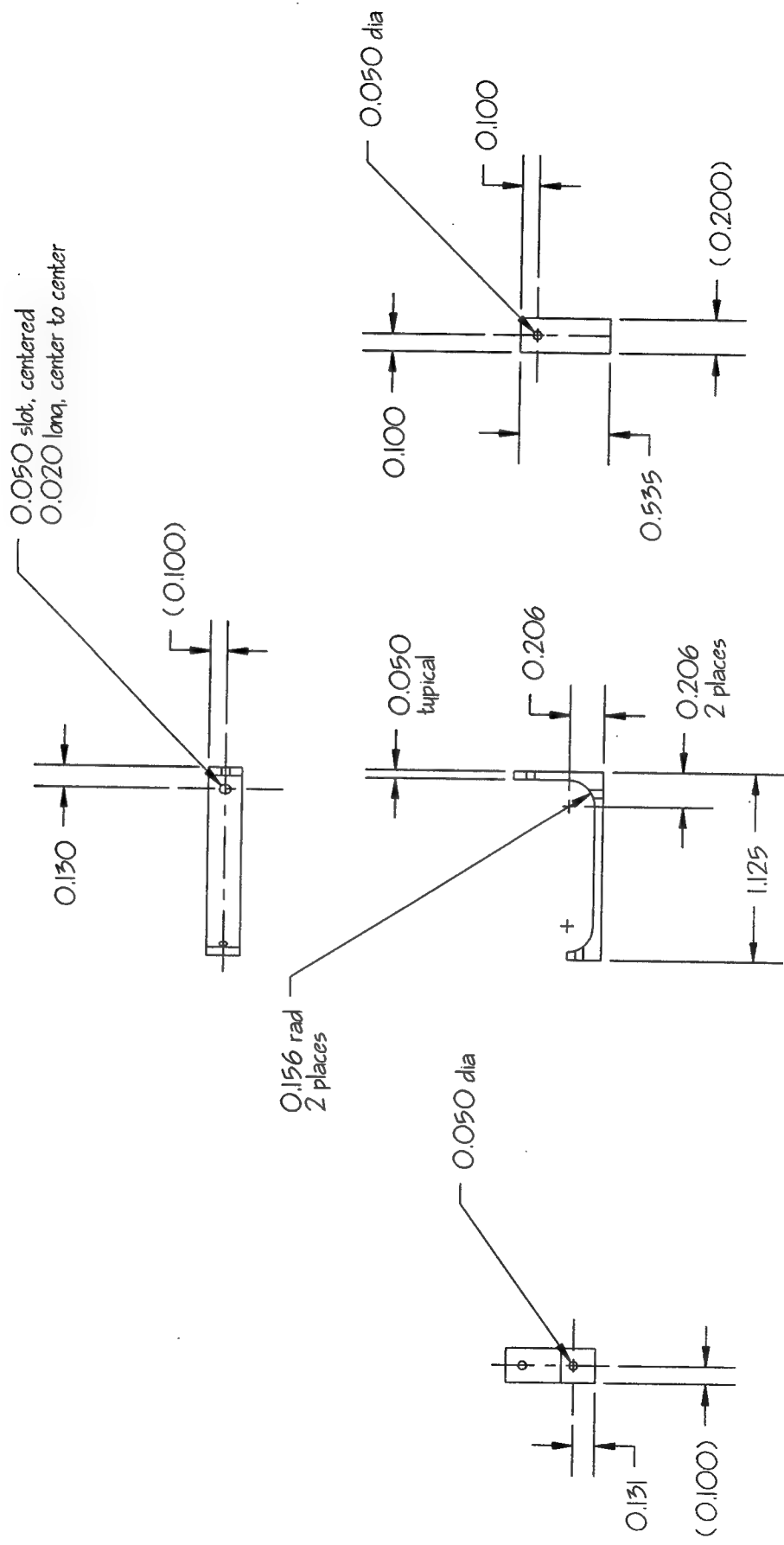
File: J-Clip: Digit #2 - Distal	Scale: 1:1	Date: 23 Mar 95	Rev: A
Drawn By: A. P. Hilton	Project: Actuator II	Release Date: 23 Mar 95	Approval:
Check: [ ]	Test: [ ]	Draw: [ ]	Rev: [ ]
Notes: [ ]	Notes: [ ]	Notes: [ ]	Notes: [ ]





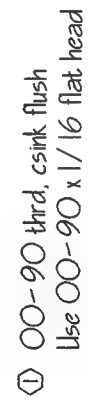
Note: Use 00-90 x 3/16 flat head screws

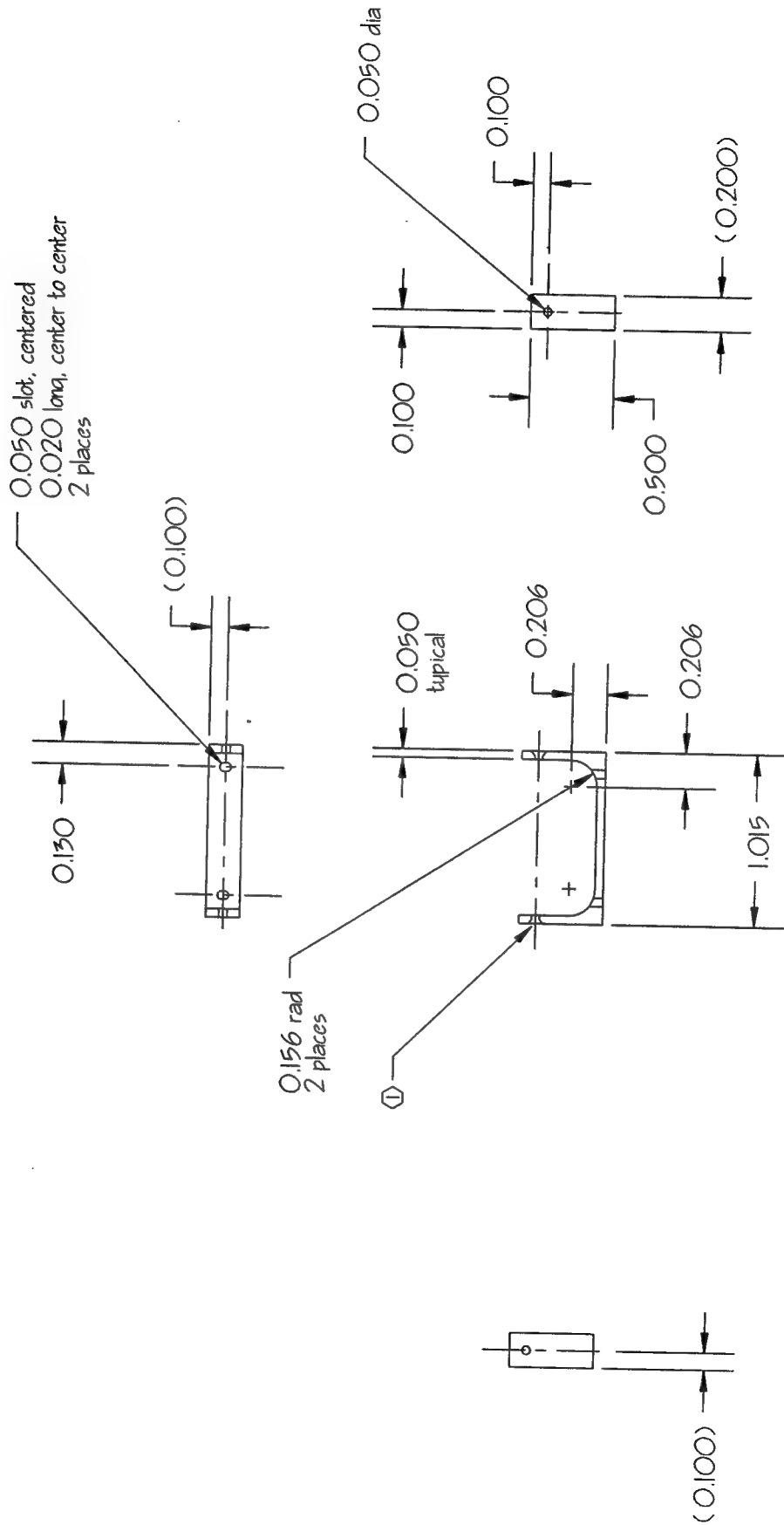
J-Clip: Digit #2 - Middle	
Scale: 1:1	Date: 24 Mar 95
Drawn By: A. P. Hilton	Release Date: 24 Mar 95
Project: Actuator II	Approval:
File Name: BE000209.dwg	
REV A	
Material: Alum	
Heat Treat: No	
Unless otherwise specified, dimensions are in inches to 3 decimal places.	



Note: Use 00-90 x 3/16 flat head screws

J-Clip: Digit #2 - Proximal	
SCALE: 1:1	DATE: 24 Mar 95
DRAWN BY: A. P. Hilton	RELEASE DATE: 24 Mar 95
PROJECT: Actuator II	APPROVAL:
FILE NAME: BE00210.dwg	
REV A	
UNLESS OTHERWISE SPECIFIED: TOLERANCES ARE IN INCHES (P. 30) DECIMALS .XX & .XX .XXX & .005	

196



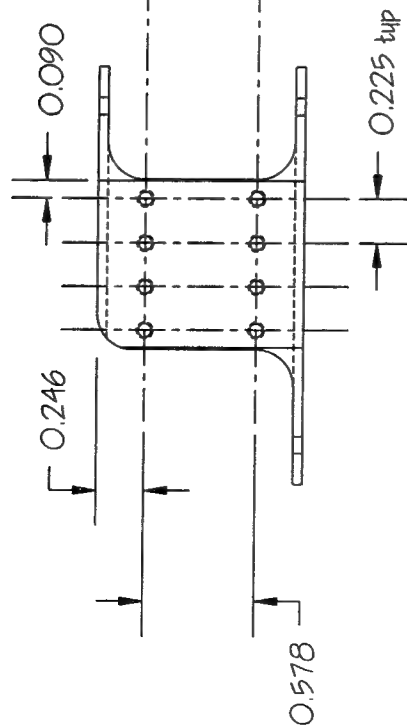
① 00-90 thrd, csink flush  
Use 00-90 x 1/16 flat head

REV A

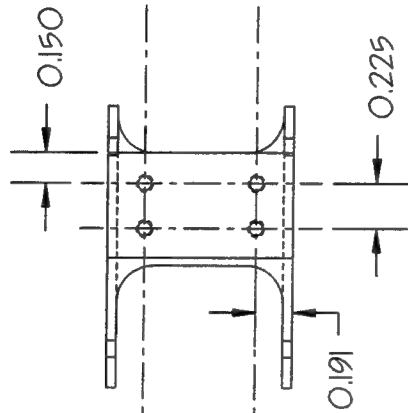
Unless otherwise specified  
Dimensions are in inches  
Tolerances on angles ± 30°  
Decimals XX ± .005

FILE NAME: BE00021.dwg  
PROJECT: ACTUATOR II  
DRAWN BY: A. P. Hilton  
DATE: 24 Mar 95  
TITLE: Modified J-Clip: Digit #2 - Middle

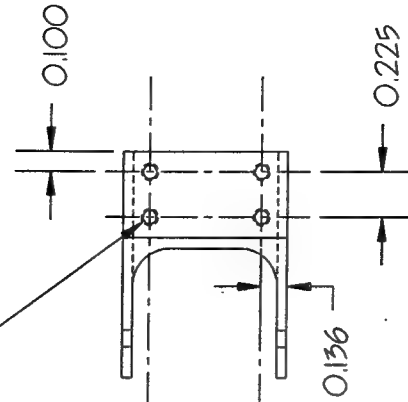
#2-56 thru thirds  
16 places



-3 BE000198



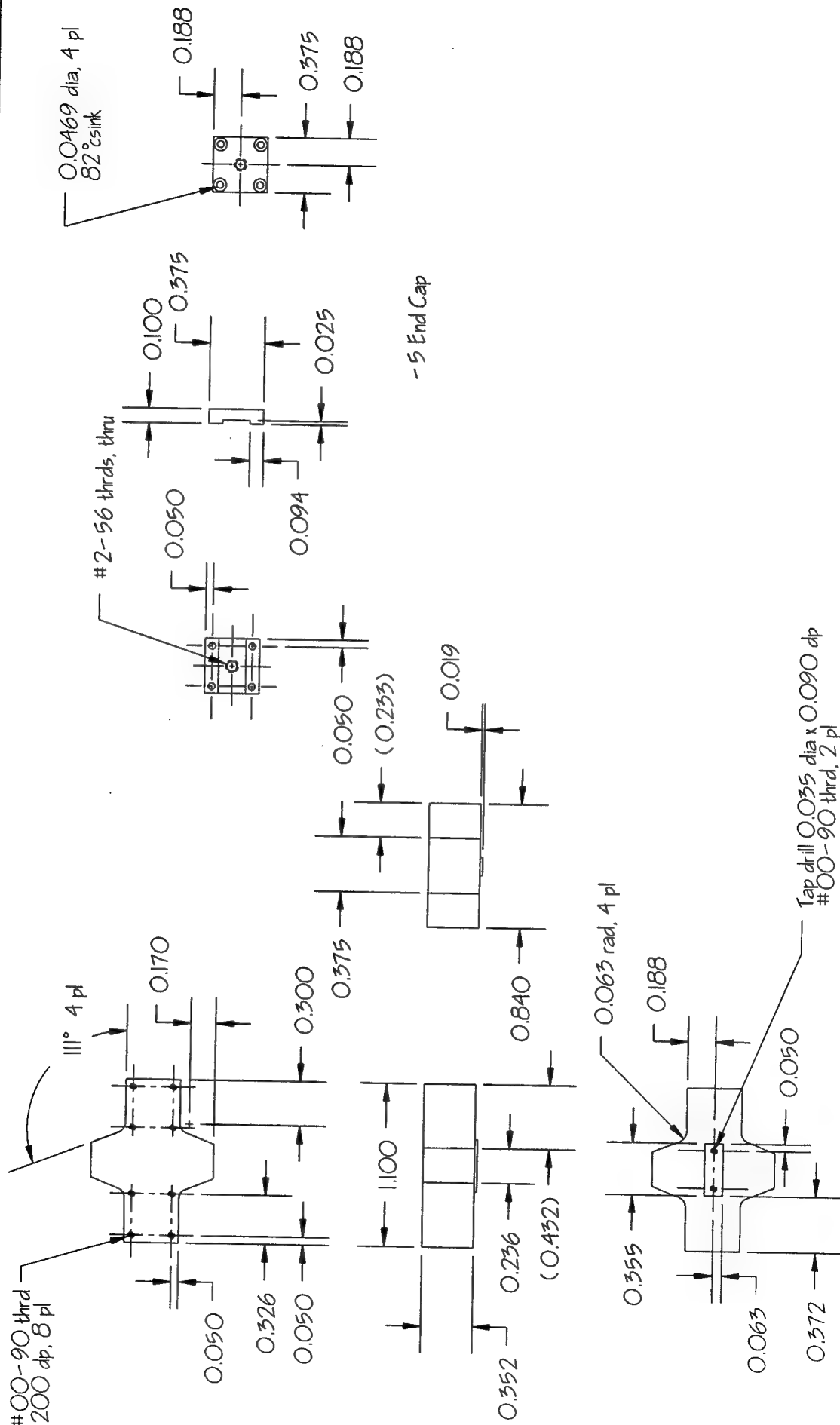
-5 BE000197



-7 BE000196

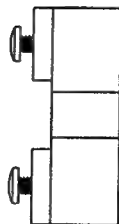
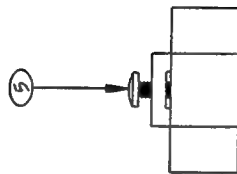
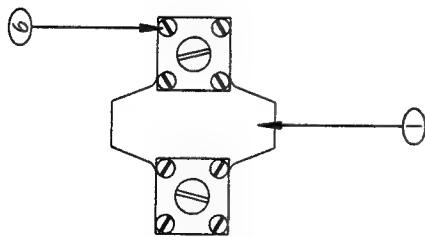
tree

TITLE: Mounting Holes Layout - Digit #2		SCALE: 1:1	DATE: 28 Mar 95	NO. BE000212
DRAWN BY: A. P. Hilton		PROJECT: Actor for II	RELEASE DATE: 28 Mar 95	APPROVAL:
REV A		POST: N/A	TEST TEST: No	
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES & DECIMALS TOLERANCES ARE AS SHOWN DECIMALS .XX & .XXX .XXX & .005				



TITLE: Pseudo Motor - Detail		SCALE: 1:1	DATE: 30 Mar 95	NO: BE000213
REV A		DRAWN BY: A. P. Hilton	DATE: 30 Mar 95	APPROVAL:
No. 1: ALU		PROJECT: Actuator II	FILE NAME: BE000213.dwg	
No. 1: ALU		FILE NAME: BE000213.dwg		

- 3 Pseudo Motor



2

Small Parts, Miami Lakes, FL 305-557-8222  
Fasteners of Comparable Spec's Acceptable

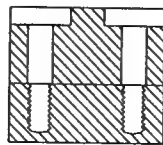
2 1  
2 1

QTY	ITEM NO.	PART NO.	DESCRIPTION	MAT'L / SPEC
2	6	MX-256-3B	#2-56 x 3/16 BH SCW	18-8 SS
8	5	MX-0090-3F	#00-90 x 3/16 FH SCW	18-8 SS
1	4	XXX	XXX	---
1	3	XXX	XXX	---
2	2	BE000215-5	End Cap	---
1	1	BE000215-5	Pseudo Motor Housing	---
---	---	BE000214	Pseudo Motor ASSEMBLY	---

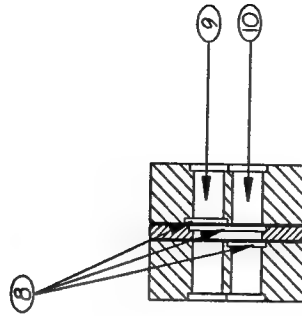
# PARTS LIST

trb

TITLE: Pseudo Motor - Assembly			
SCALE: 1:1	DATE: 30 Mar 95	REV: A	REV: BE000214
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON ANGLES ± 0° DECIMALS XX ± .XX XXX ± .005	DRAWN BY: A. P. Hilton	PROJECT: Actuator II	RELEASE DATE: 30 Mar 95
		FILE NAME: BE000214.dwg	APPROVAL:



Section A-A




Section B-B

2	10	521440-002	Photo Detector	---
2	9	5E1450-005	LED	---
3	8	XXX	Polarizing Filter	---
2	7	MX-080-4B	# 0-80 x 1/4 Prod. Hd Screws	18-B.55
1	6	DWV-1-4	1/16 Dia 1/4 Dowel Pin	303.55
1	5	XXX	XXX	---
1	4	XXX	XXX	---
1	3	PE000217	Clip	---
1	2	PE000218	Proximal Section	---
1	1	PE000216	Distal Section	---
---	---	PE000215	ANGLE SENSOR ASSEMBLY	---
QTY REQD	ITEM NO.	PART NO.	DESCRIPTION	MAT'L / SPEC

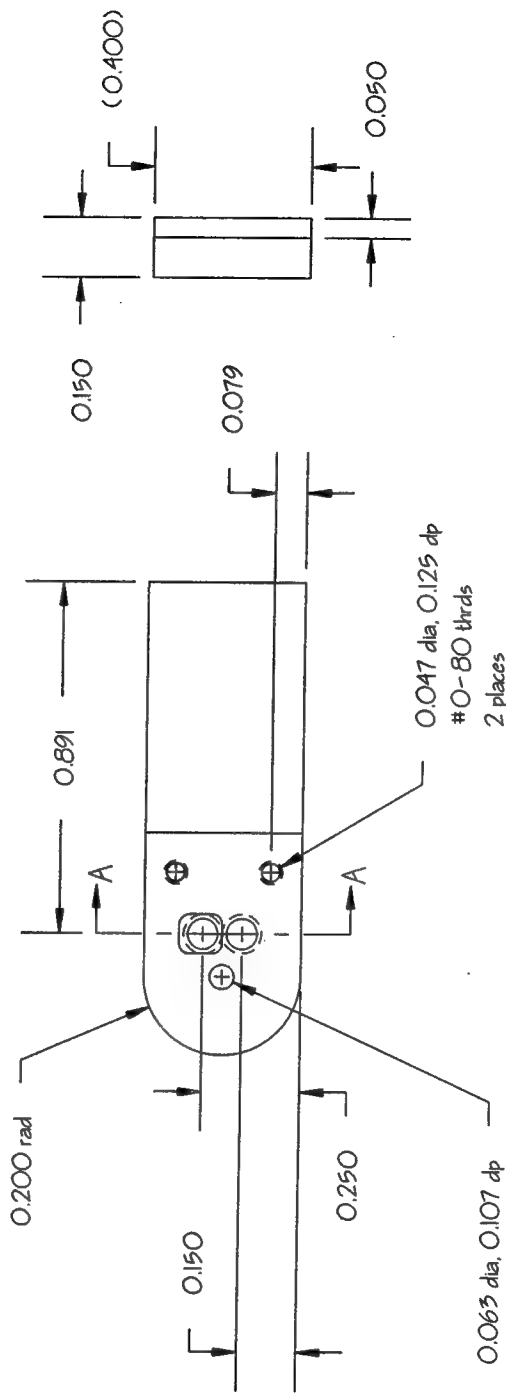
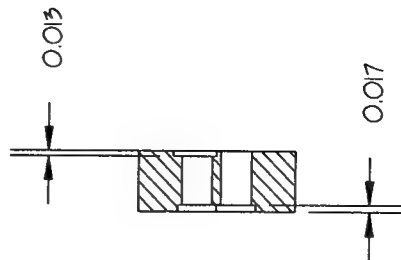
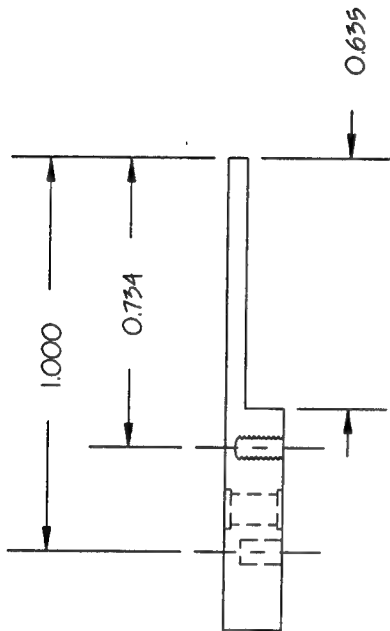
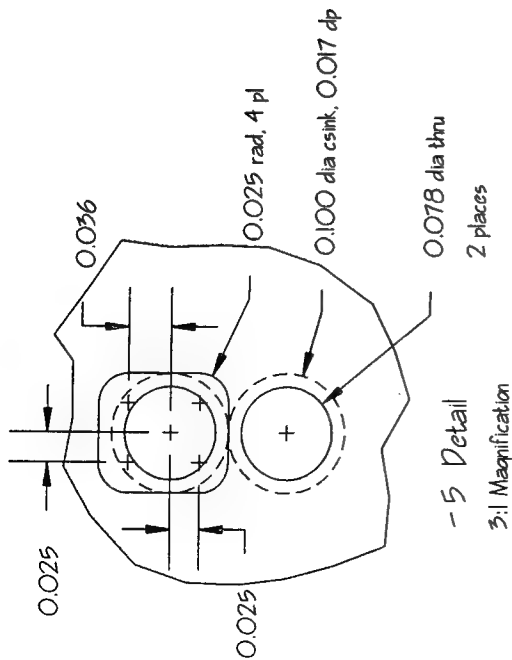
## PARTS LIST



		<b>THE Angle Sensor - Assembly</b>	
Unless otherwise specified Dimensions are in inches Tolerances on angles & 0° Min/Max .XX ± .02, .XXX ± .005		<b>REV A</b>	SCALE: 2:1    DATE: 6 Apr. 95    No. BE000215
Heat Treat - No		DRAWN BY: A. P. Hilton	RELEASE DATE: 6 Apr. 95
Heat Treat - No		PROJECT: Actuator II	APPROVAL:
Heat Treat - No		TLE NAME: be00215.dwg	

Small Parts, Miami Lakes, FL 305-557-8222  
Fasteners of Comparable Spec's Acceptable  
Marshall  
Visual Pursuits, Inc.





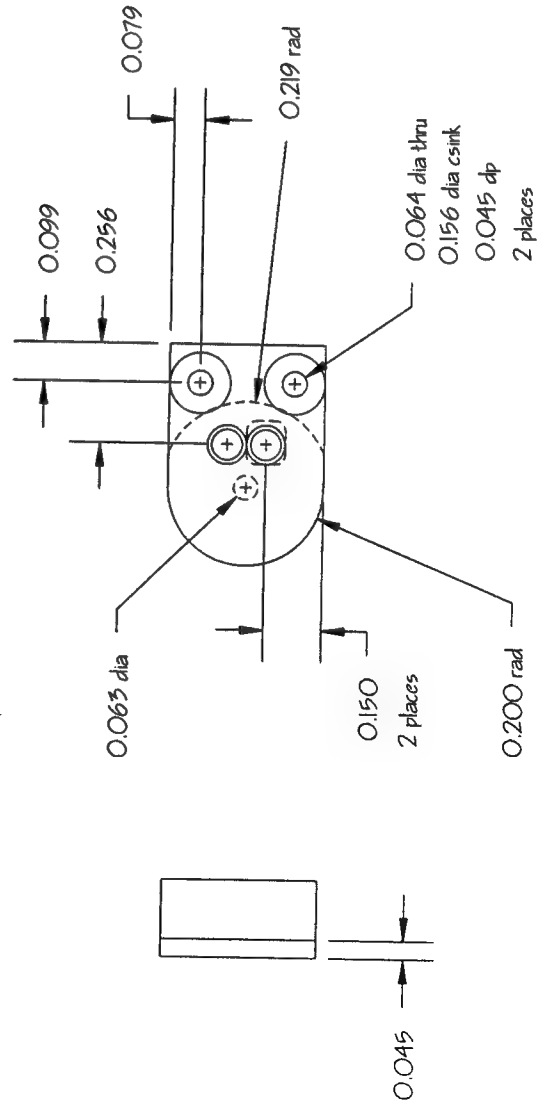
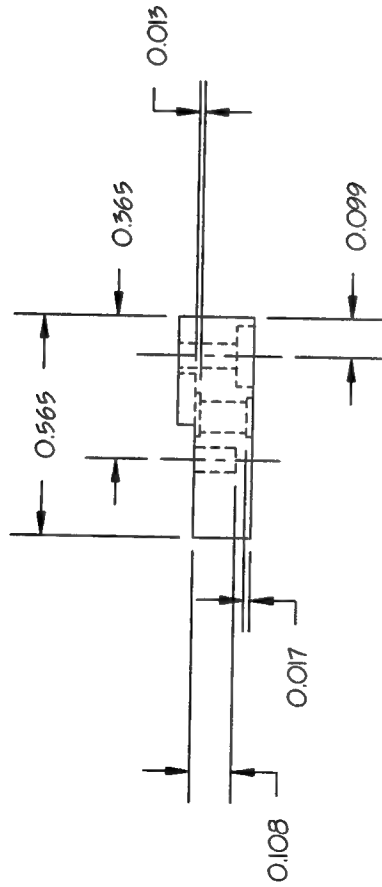
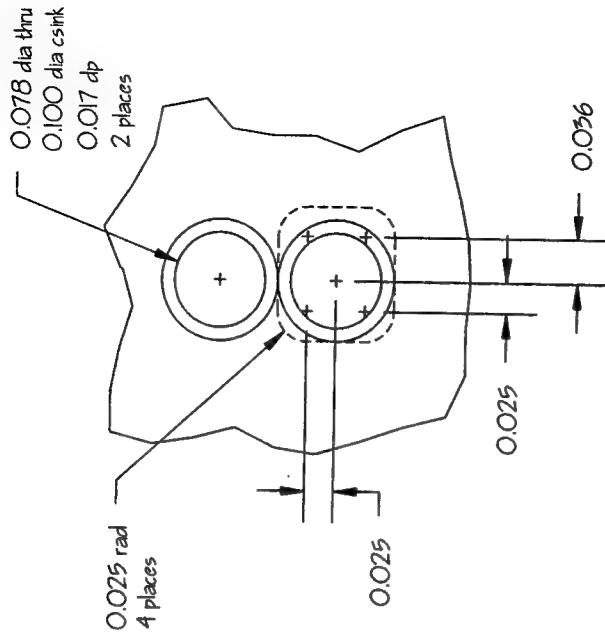
trc

FILE	Angle Sensor - Detail Distal
SCALE	2:1
DATE	3 Apr 95
DESIGN BY	A. P. Hilton
PROJECT	Actuator II
FILE NAME	BE000216.dwg

-3 Distal Section

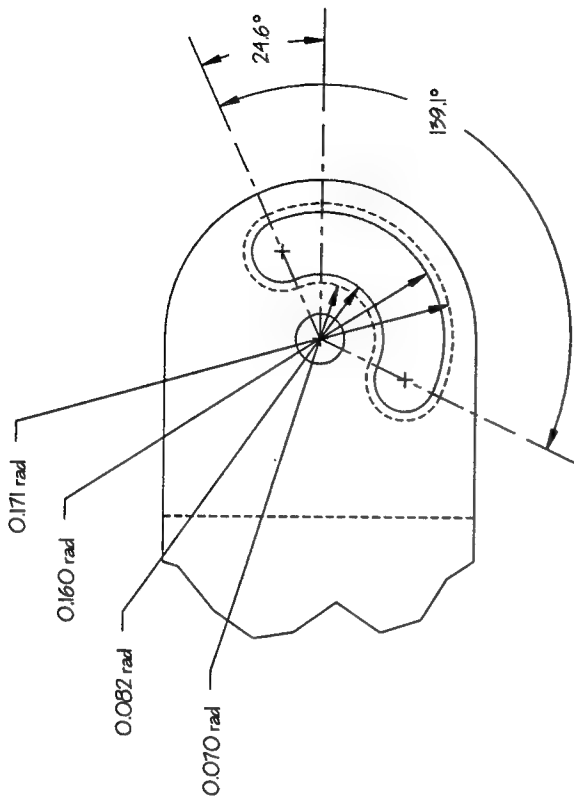
Unless otherwise specified  
Dimensions are in inches  
Tolerances on angles ± 0° 30'  
Decimals XX ± .02, .01, .005

REV	A
DATE	3 Apr 95
BY	AP
CHKD	AP
APPV	AP

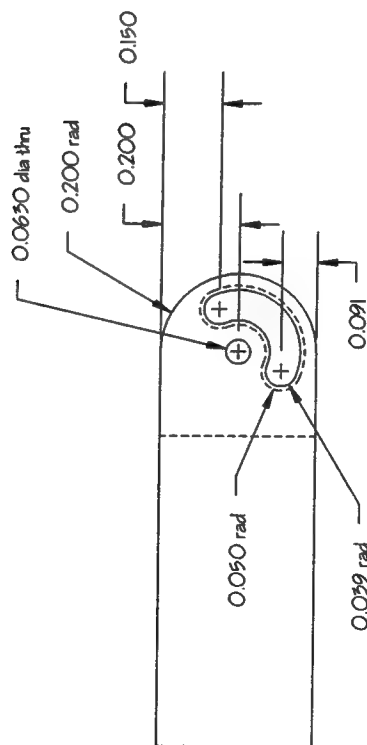
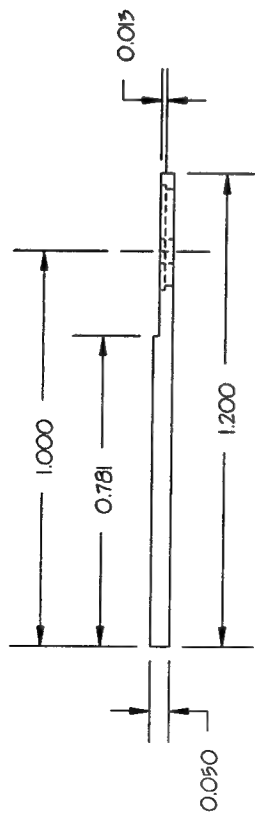
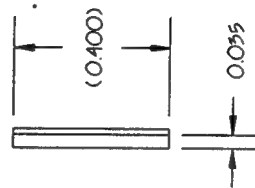


tree

TITLE: Angle Sensor - Detail; Clip		SCALE: 2:1	DATE: 6 Apr 95	NO: BE000217
REV: A		DRAWN BY: A. P. Hilton	RELEASE DATE:	
PROJECT: Actuator II		PROJECT ACTUATOR II	APPROVAL:	
FILE NAME: be000217.dwg		DESIGNER: A. P. Hilton	DATE: 6 Apr 95	



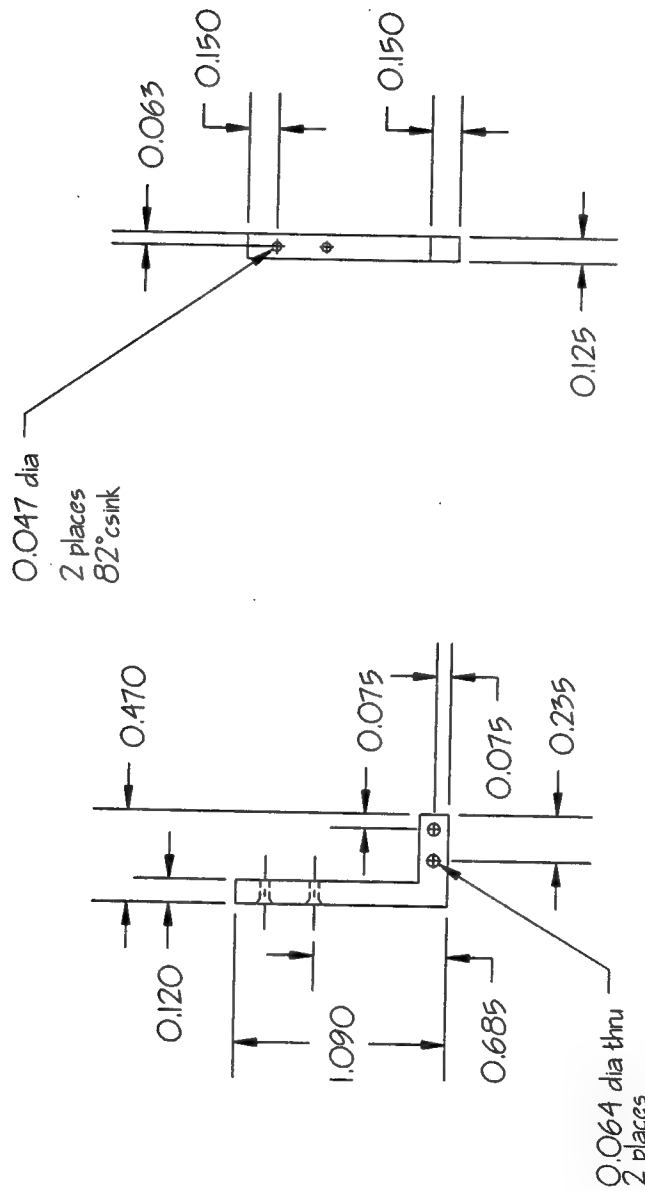
-5 Detail  
2:1 Magnification



-3 Proximal Section

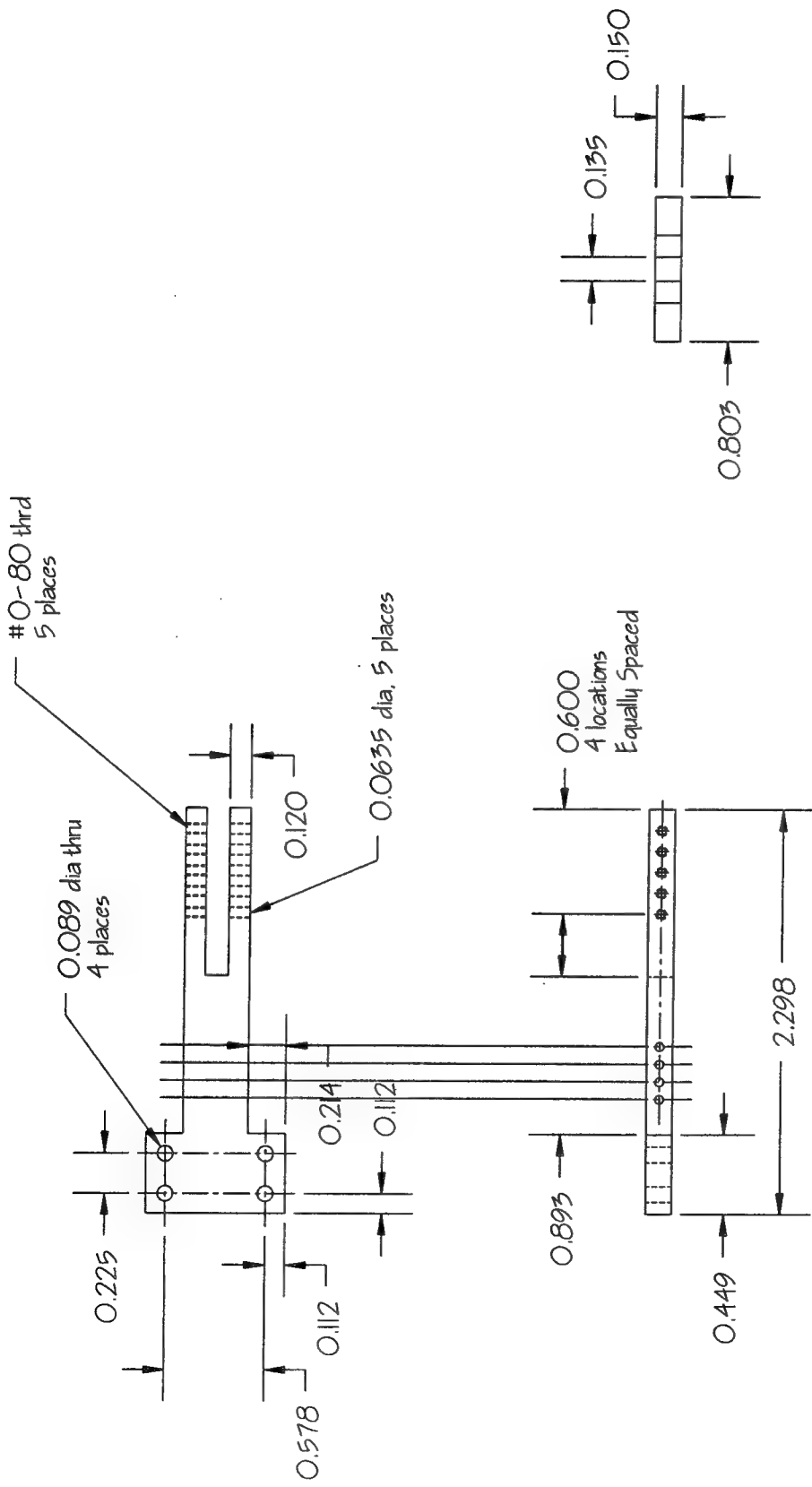
tr

TITLE: Angle Sensor - Detail: Proximal		SCALE: 2:1	DATE: 6 Apr 95	REV: A	DRWN BY: A. P. Hilton	DATE: 6 Apr 95	FILE NAME: be000218.dwg
UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES, DECIMALS SIX (6) DIGITS.		PROJECT: Actuator II		APPROVAL:			
REV: A		MATERIAL: ALUM		MATERIAL: ALUM			
		MATERIAL: ALUM		MATERIAL: ALUM			



tree

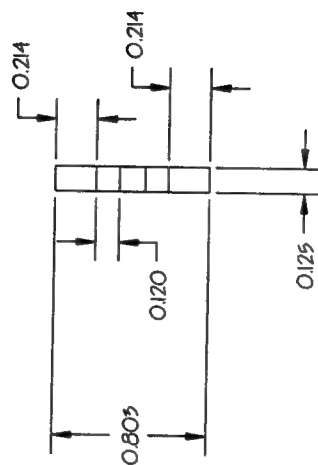
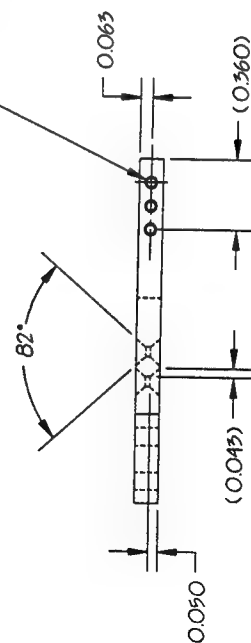
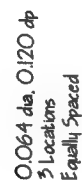
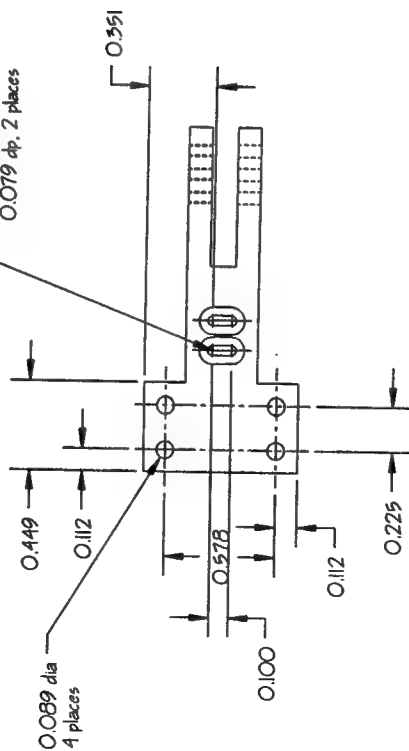
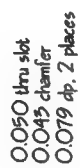
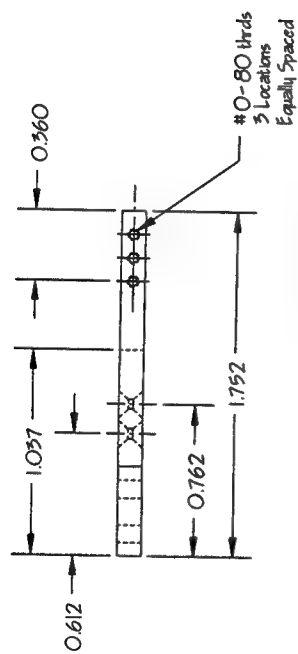
TITLE: 'L' Angle - Motor Mount		DATE: 11 Apr 95		No. BE000219	
SCALE: 1:1		DRAWN BY: A. P. Hilton		CHECKED BY: 14 Apr 95	
PROJECT: Actuator II		FILE NAME: be00219.dwg		APPROVAL:	
REV B		REV B		REV B	
REV B		REV B		REV B	
REV B		REV B		REV B	
REV B		REV B		REV B	
REV B		REV B		REV B	
REV B		REV B		REV B	
REV B		REV B		REV B	



123

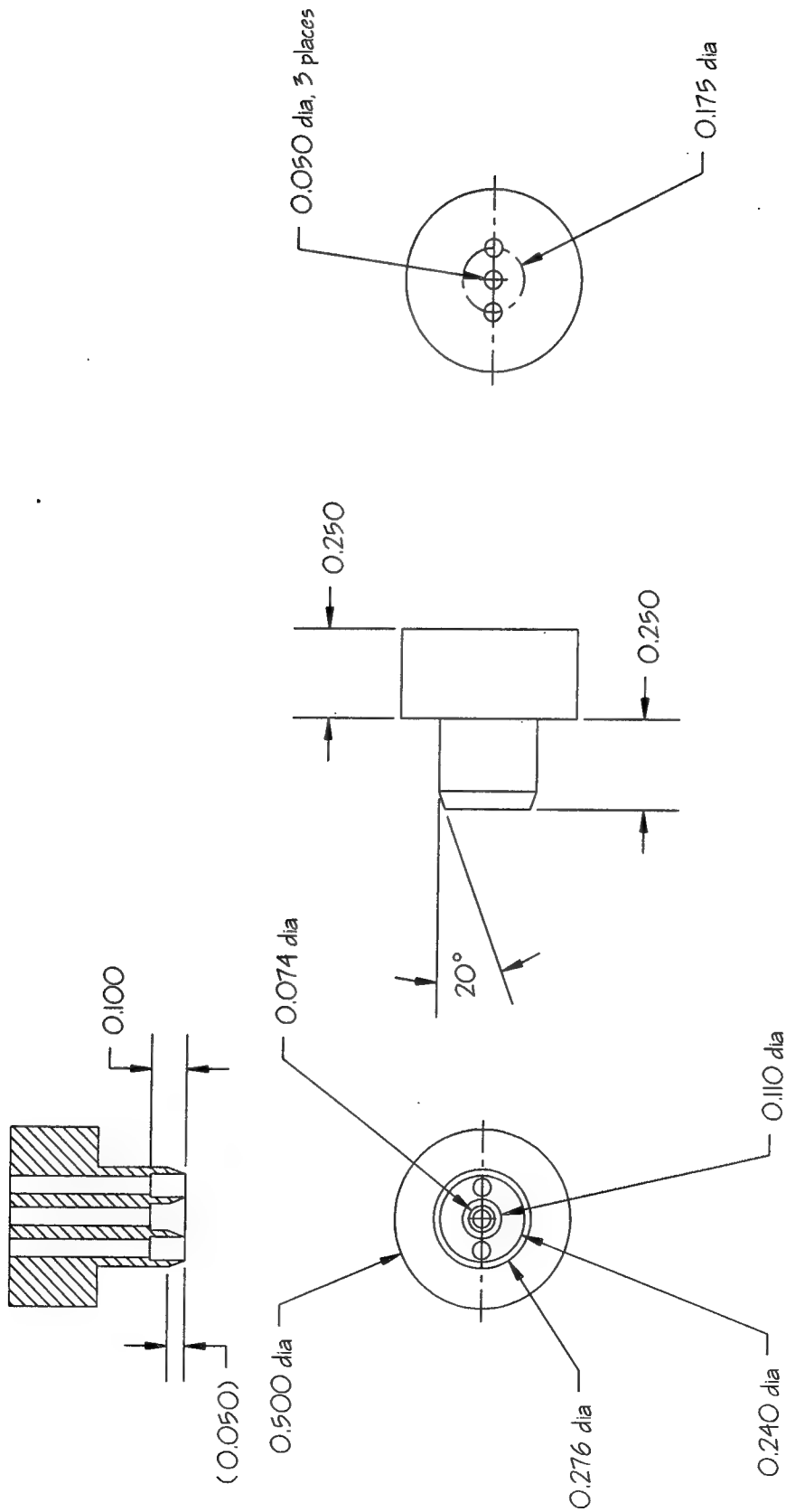
Title: Cantilever - Proximal 2			
Scale: 1:1	Date: 11 Apr 95	Rev: BE000220	Release Date: 11 Apr 95
Drawn By: A. P. Hilton	Project: Actuator II	Approval:	
Check: [blank]	Heat Treat: No	Decimals: .XX ± .03, .XXX ± .005	File Name: BE000220.dwg

Unless otherwise specified  
Dimensions are in inches  
Tolerances on angles ± 0° 30'  
Decimals .XX ± .03, .XXX ± .005



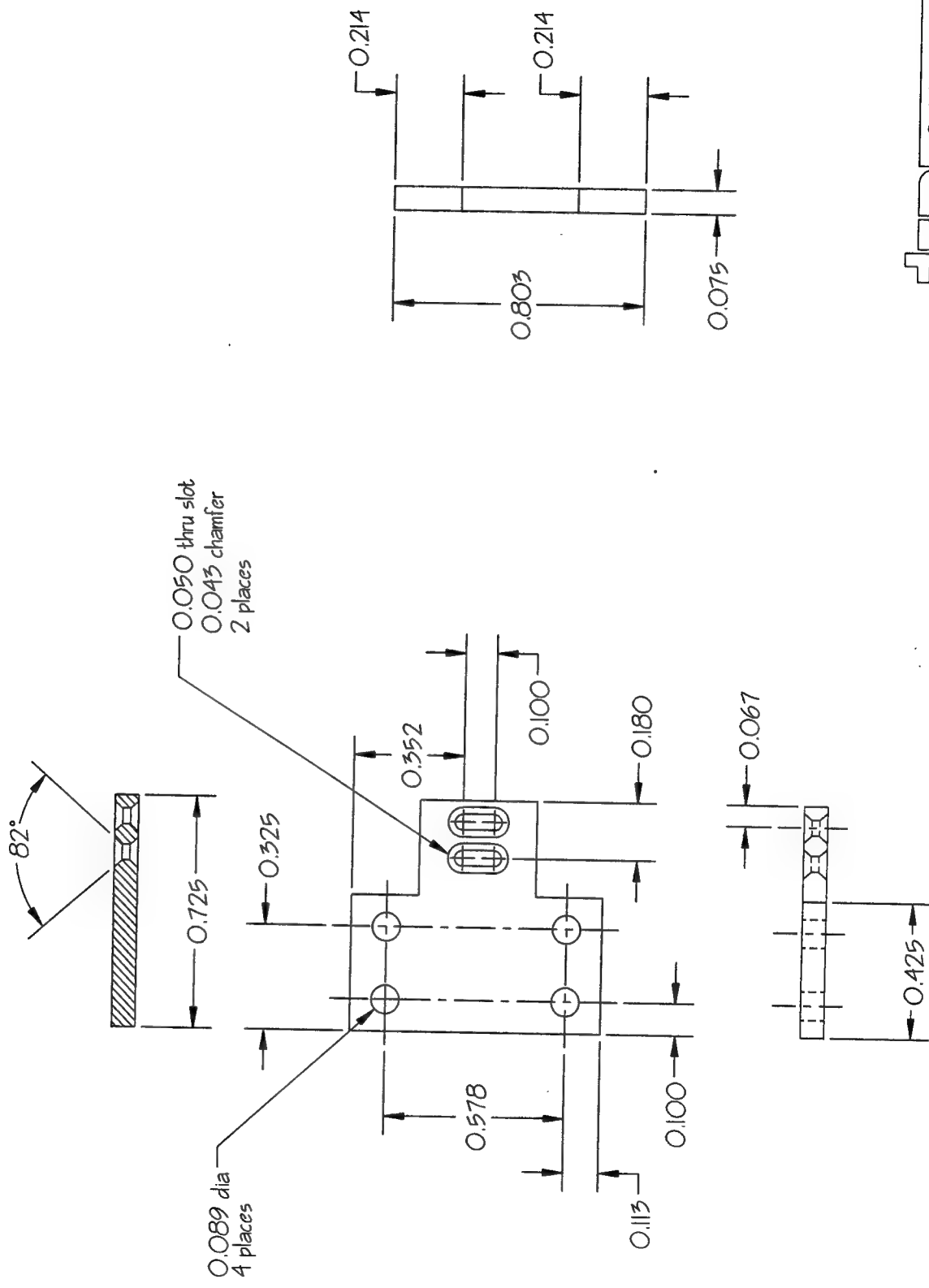
10

TITLE: Cantilever - Middle 2	
SCALE: 1:1	DATE: 13 Apr 95
DRAWN BY: A. P. Hilton	Mo: BE000222
PROJECT: Actuator II	RELEASE DATE: 13 Apr 95
FILE NAME: be0022.dwg	APPROVAL:



tra

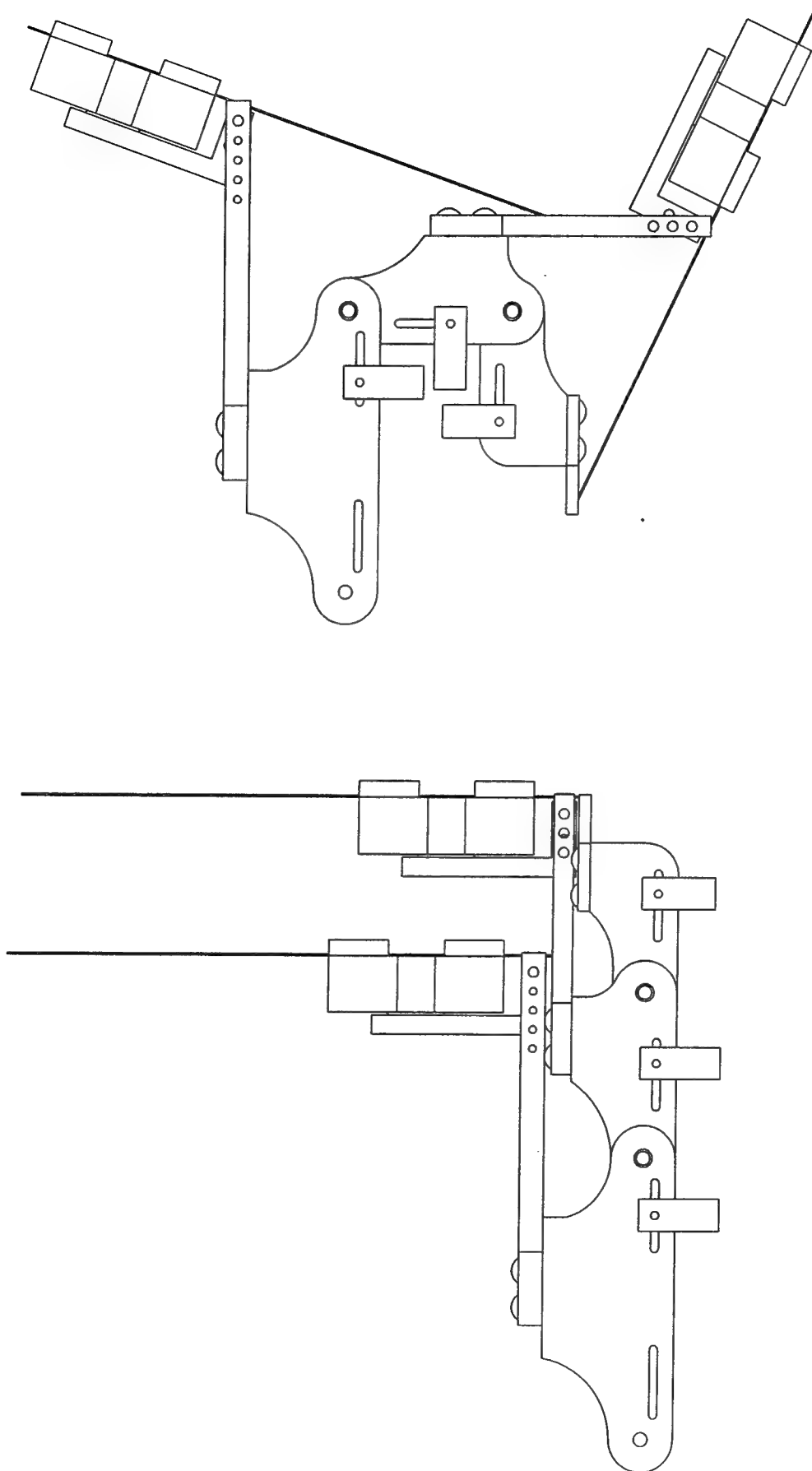
Punch - Teflon Washer	
SCALE: 1:1	DATE: 14 Apr 95
REV A	DESIGN BY: A. P. Hilton
REV A	PROJECT: Actuator II
REV A	FILE NAME: be000223.dwg
REV A	RELEASE DATE: 14 Apr 95
REV A	APPROVAL:



trc

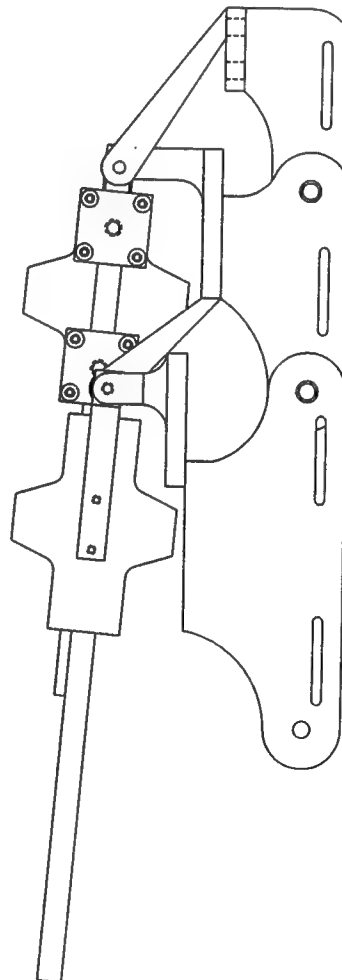
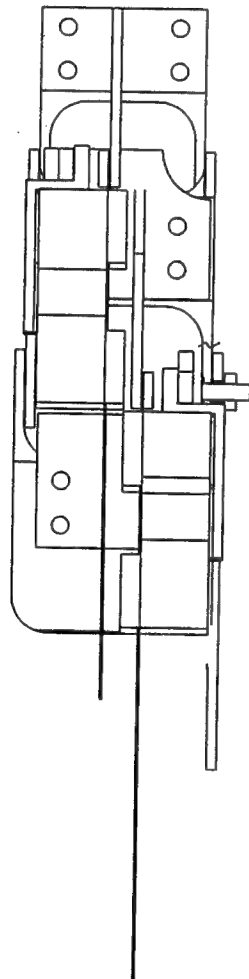
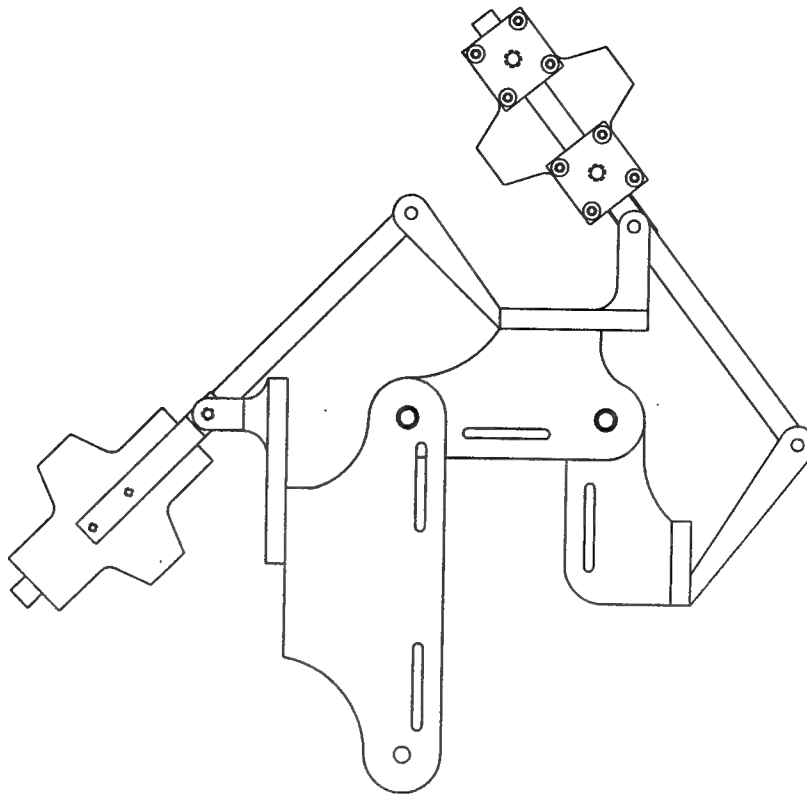
TITLE: Distal Cantilever - Digit #2		SCALE: 2:1	DATE: 14 Apr 95	W. BE 000224
REV A		DRAWN BY: A. P. Hilton	PROJECT: Actuator II	RELEASE DATE: 14 Apr 95
No. 1: ALU		PROJECT: Actuator II	FILE NAME: W00224.dwg	APPROVAL
No. 2: ALU		PROJECT: Actuator II	FILE NAME: W00224.dwg	APPROVAL





trc

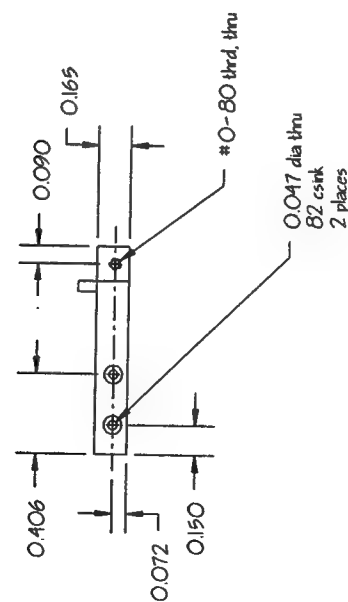
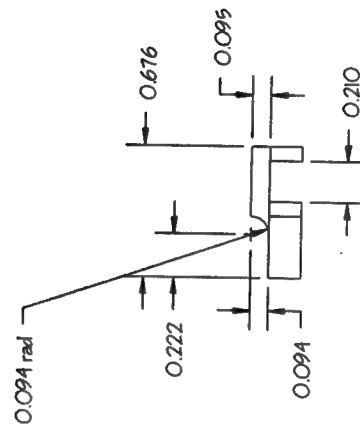
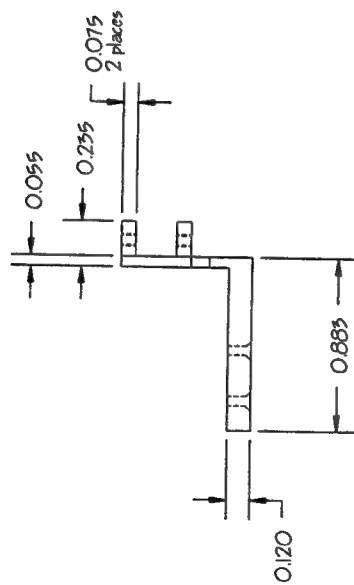
TITLE: Assembly - Digit 2; with Motors		SCALE: 1:1	DATE: 20 Apr 95	REV: BE000225
DRAWN BY: A. P. Hilton		PROJECT: Actuator II		RELEASE DATE: 20 Apr 95
PROJECT: Actuator II		FILE NAME: be000225.dwg		APPROVAL:
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES DECIMALS ARE TO 0.005 TOLERANCES ARE: FRACTIONS: .005 DECIMALS: .005 HOLE TOLERANCE: .005		REV: B	DATE: 20 Apr 95	REV: BE000225
PROJECT: Actuator II		FILE NAME: be000225.dwg		APPROVAL:




trc

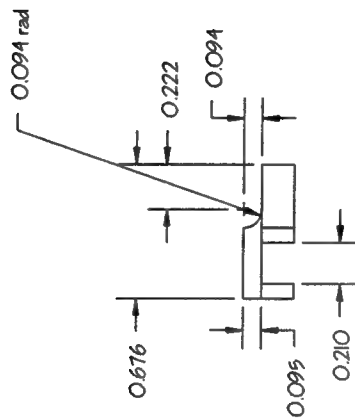
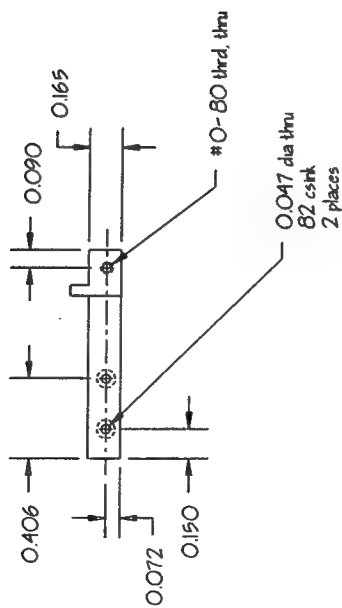
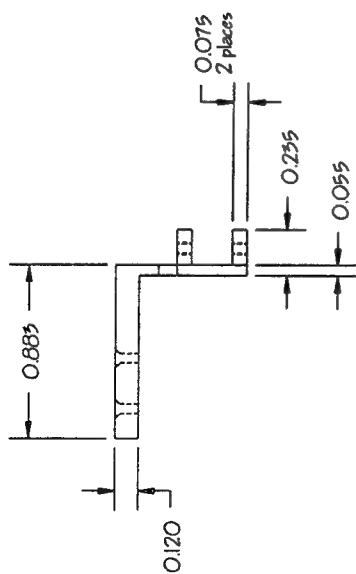
TITLE: Assembly - Digit 2- 3rd Iteration		SCALE: 1:1	DATE: 24 Apr 95	IN: BE000230
DRAWN BY: A. P. Hilton		PROJECT: ACTUATOR II		FILE NAME: be000230.dwg
REV A		MATERIAL: 304 SS		APPROVAL:
MATERIAL: 304 SS		MATERIAL: 304 SS		APPROVAL:
MATERIAL: 304 SS		MATERIAL: 304 SS		APPROVAL:





- 3 - Proximal "F" Clip

		TITLE: Proximal "F" Clip SCALE: 1:1 DATE: 21 Apr 95 DRAWN BY: A. P. Hilton PROJECT: Actuator II FILE NAME: DE00227.dwg	
REV A Multi: Alum Next: Trex: 1 No.		No. BE000227 RELEASE DATE: 21 Apr 95 APPROVAL:	

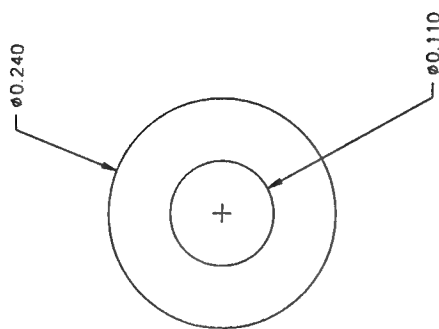


-3 - Middle "F" Clip

REV A

FILE NAME: M0028.dwg

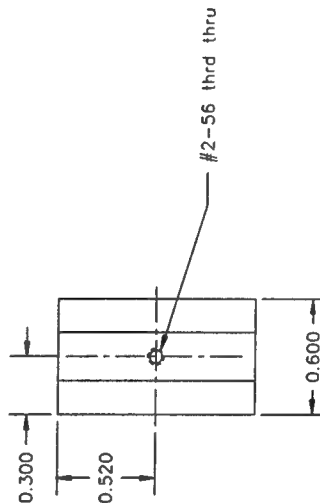
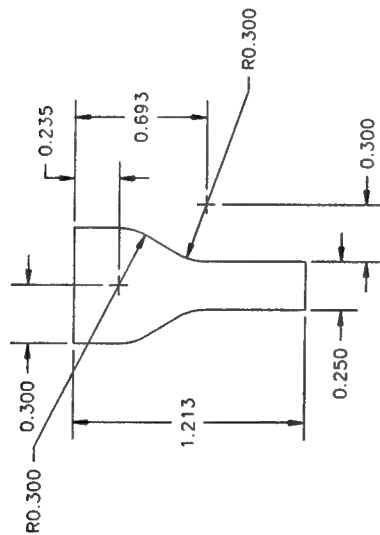
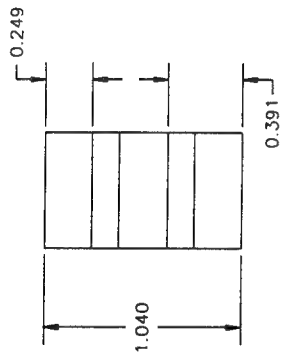
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON DIMENSIONS ARE: FRACTIONS DECIMALS ANGLES	REV A	FILE NAME: M0028.dwg
Math: ALUM	PROJECT: ACTUATOR II	APPROVAL:
Next Trans: No		
	DATE: 21 Apr 95	SCALE: 1:1
	DRAWN BY: A. P. Hilton	TITLE: Middle "F" Clip
		NO: BE000228
		RELEASE DATE: 21 Apr 95



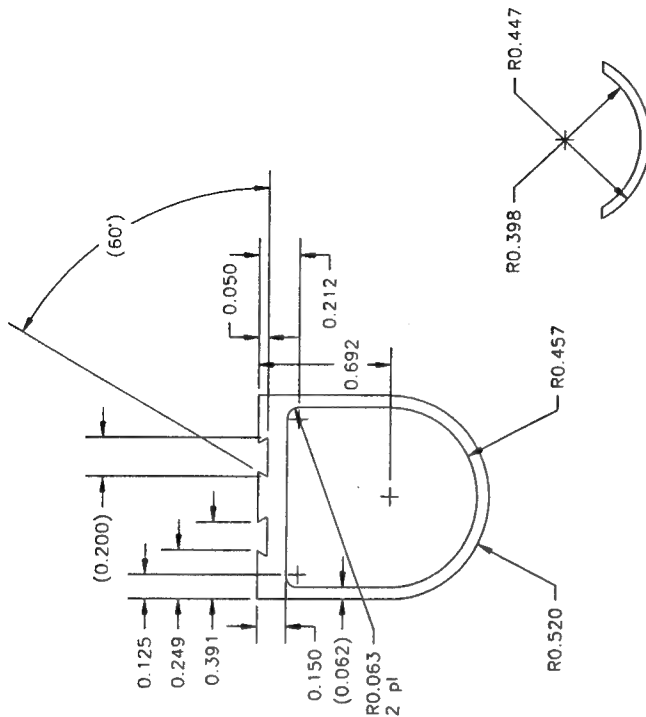
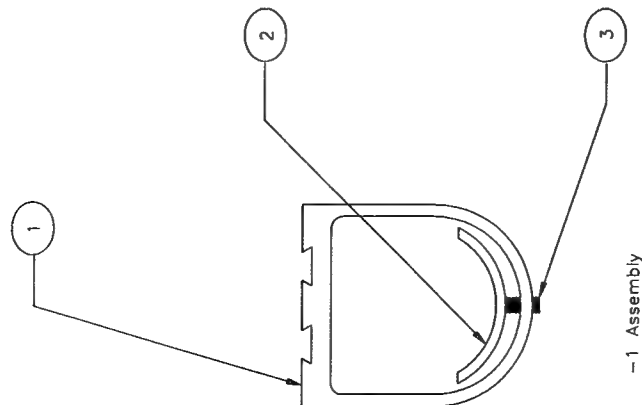
- ② Use 0.005" teflon sheet  
Small Parts Inc., Miami Lakes, FL 1-800-423-9009  
Part No: A-VT-5  
Punch with BE000223
- ①

tra

TITLE: Washer, Motive Cell End Cap		No. BE000264	
SCALE: 10:1	DATE: 21 Aug 95	RELEASE DATE: 21 Aug 95	
DRAWN BY: A. P. Hilton		APPROVAL:	
PROJECT: Actuator II		FILE NAME: BE00264.dwg	
Rev A		C	
Unless otherwise specified: Dimensions are in inches		Heat Treat:	
Tolerances on angles ± 0° 30'		Matl:	
Decimals .XX ± .03, .XXX ± .005			



-3 Ring Detail



-5 Clamp Detail

QTY	ITEM	PART	DESCRIPTION	MAT'L/SPEC
1	5	XXX	XXX	---
1	4	XXX	XXX	---
1	3	SSAS-256-3	#2-56 x 3/16 set screw	---
1	2	BE000265-5	Adjustment Clamp	---
1	1	BE000265-3	Ring	---
1	---	BE000265	RING ASSEMBLY	---

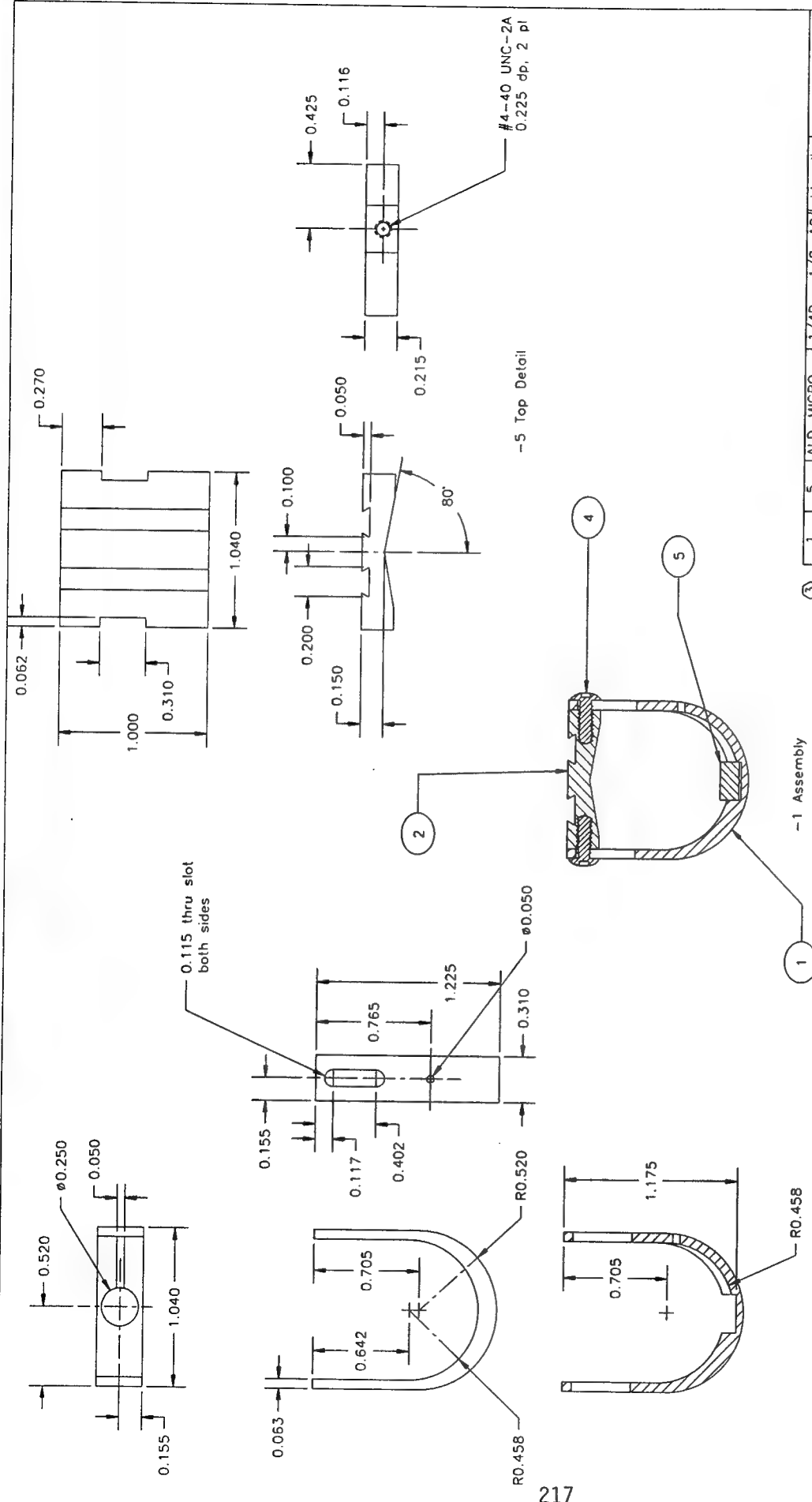
(1)(2)

② Fasteners of comparable spec's acceptable.  
① Small Parts Inc., Miami Lakes, FL 1-800-220-4242

# PARTS LIST

tra

TITLE: Ring Mount - PIP; Exoskeleton		SCALE: 2:1	DATE: 22 Aug 95	No. BE000265
DRAWN BY: A. P. Hilton		RELEASE DATE: 22 Aug 95		
PROJECT: Actuator II		APPROVAL: C		
FILE NAME: BE000265.dwg				



QTY	ITEM REQD	NO.	PART NO.	DESCRIPTION	MAT'L/SPEC
1	5	ALD-MICRO	1/40 x 1/8, 10# id cell	---	---
2	4	4C25KBCY	#4-40 x 1/4 Bln Soc Cap	SS	---
1	3	XXX	---	---	---
1	2	BE000265-5	Ring Top	Delrin	---
1	1	BE000265-3	Ring Base	Delrin	---
1	---	BE000265	RING ASSEMBLY	---	---

③  
①②

③ AL Design, Inc., 1411 Military Rd, Buffalo, NY 716-875-6240  
 ② Fasteners of comparable spec's acceptable.  
 ① ABABA Bolt Inc., El Cajon, CA (619) 440-1781

# PARTS LIST

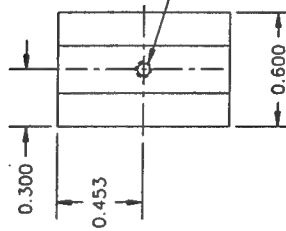
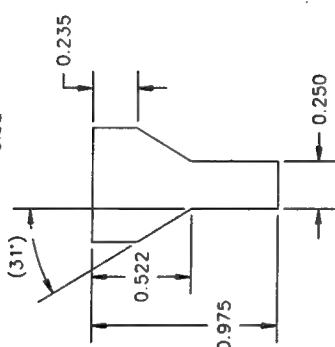
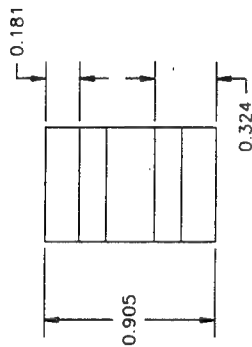
tra

TITLE: Ring Mount - PIP; Exoskeleton  
 SCALE: 2:1 DATE: 22 Aug 95 No. BE000265  
 DRAWN BY: A. P. Hilton RELEASE DATE: 17 Oct 95  
 PROJECT: Actuator II APPROVAL: C  
 FILE NAME: BE00265.dwg

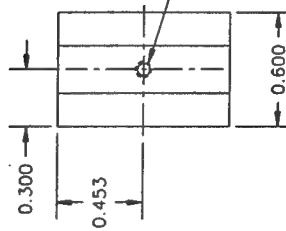
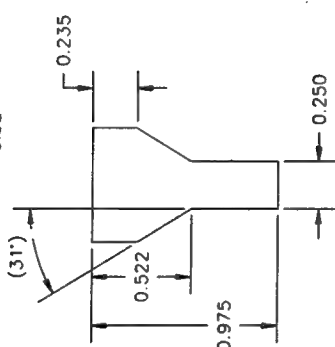
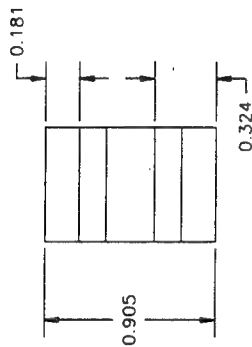
Rev D	Matl: Delrin	Heat Treat: N/A
1	1	1

NO.	REVISION	DATE	BY
3	length of top section	17 Oct 95	APH
2	two piece adjustable, load cell mount	14 Sep 95	APH
1	height, clamp pos, load cell mnt, strain relief	12 Sep 95	APH

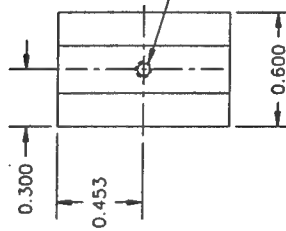
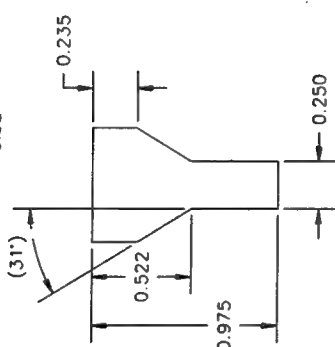
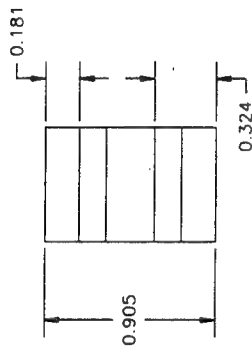




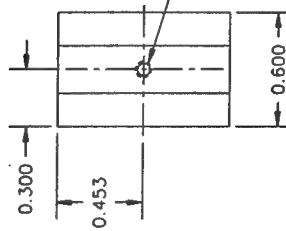
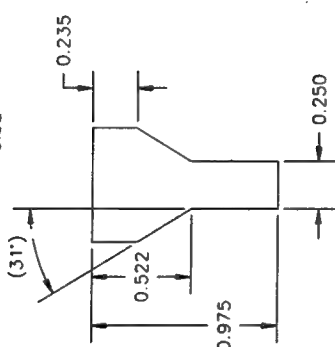
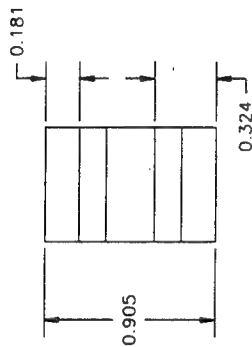
-3 Ring Detail



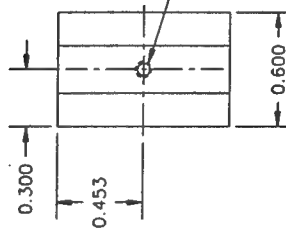
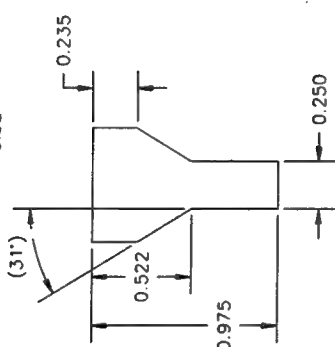
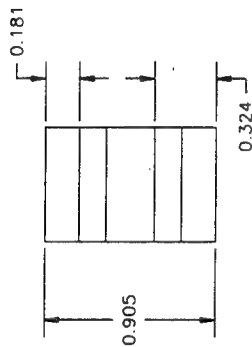
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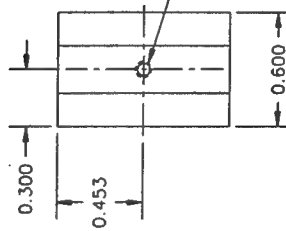
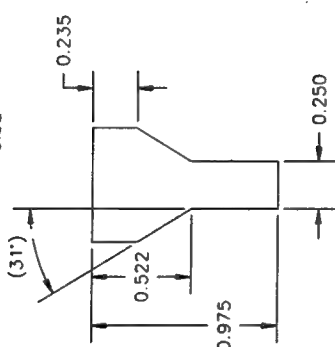
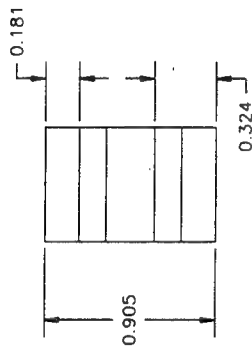
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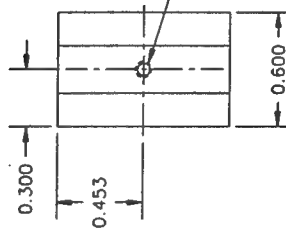
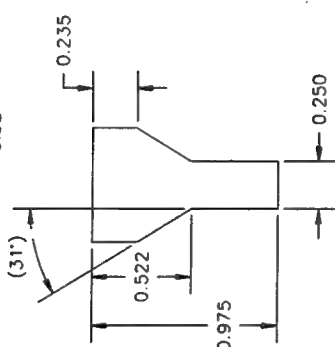
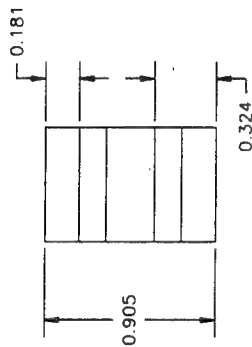
-3 Ring Detail



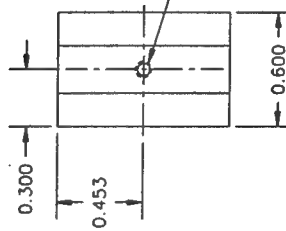
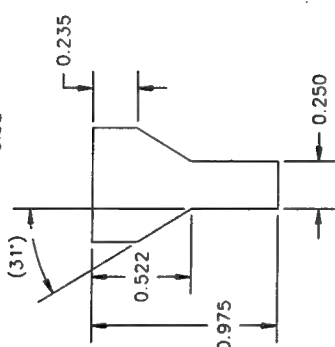
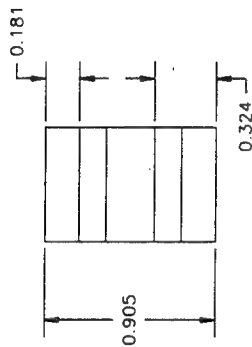
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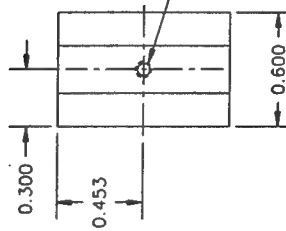
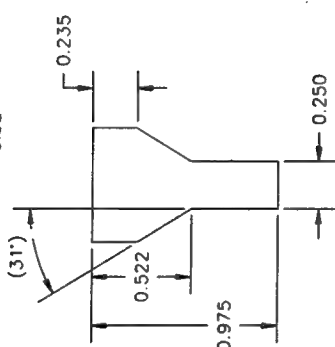
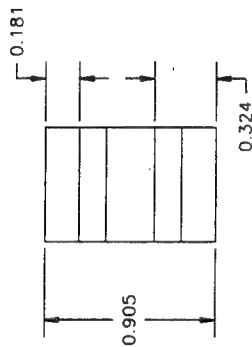
-3 Ring Detail



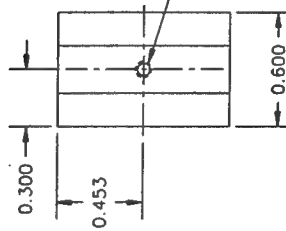
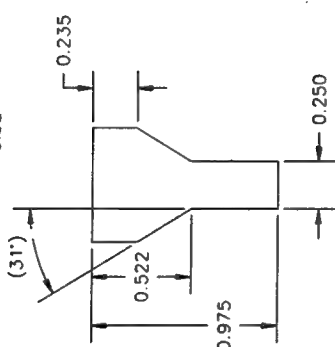
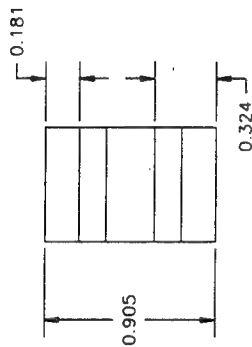
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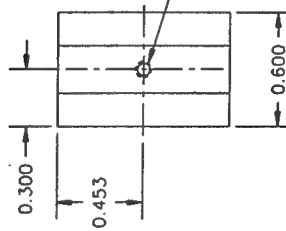
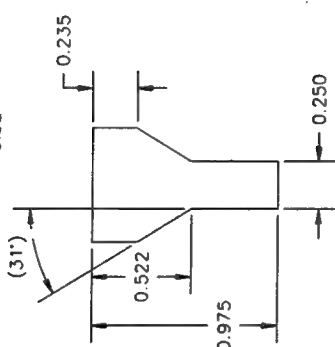
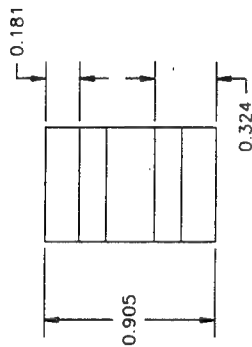
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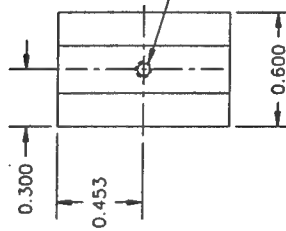
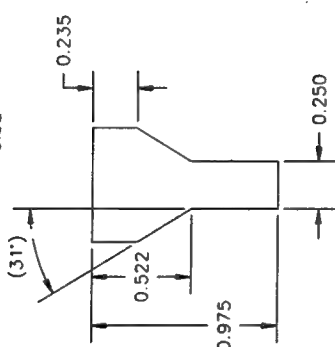
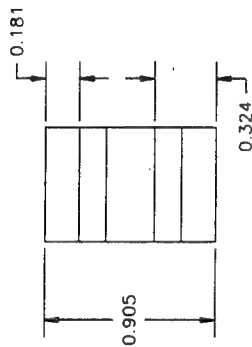
-3 Ring Detail



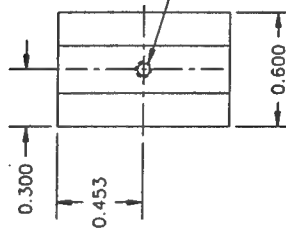
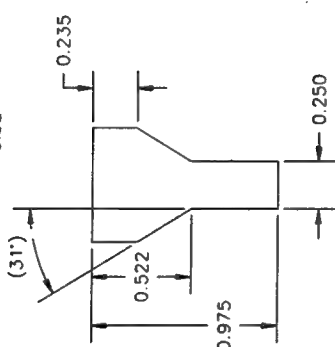
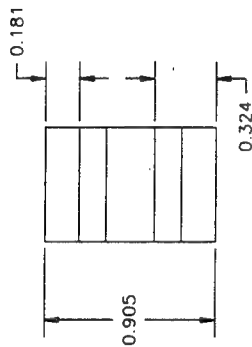
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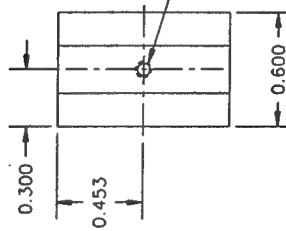
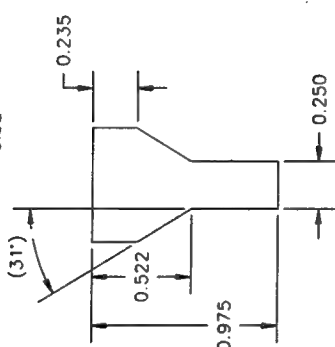
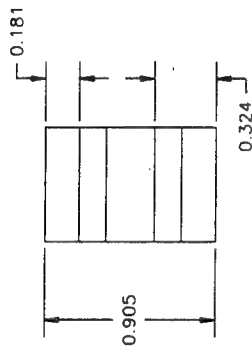
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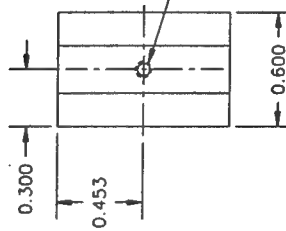
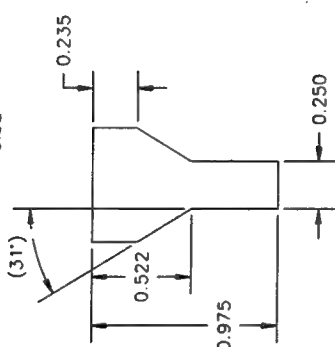
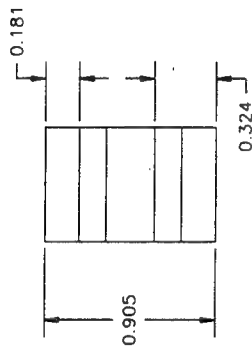
-3 Ring Detail



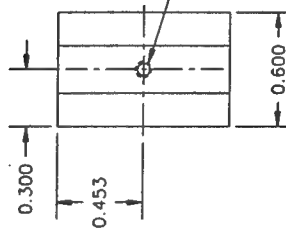
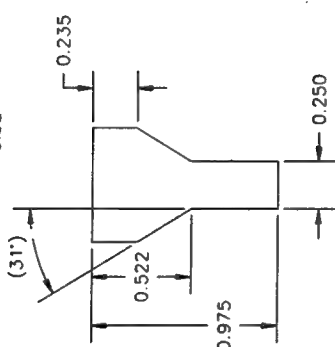
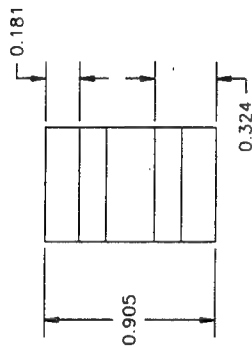
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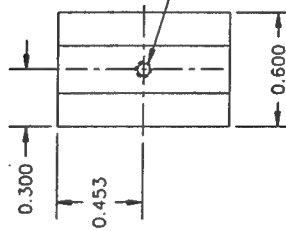
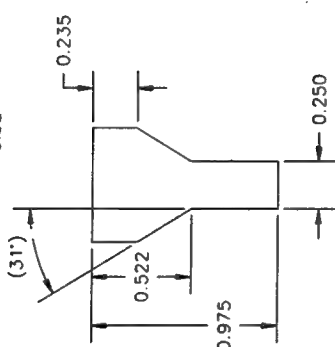
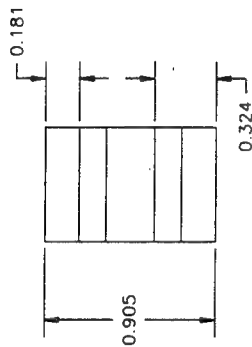
-3 Ring Detail



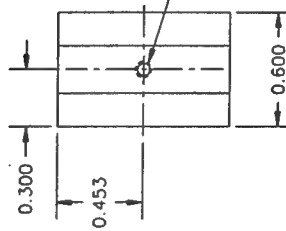
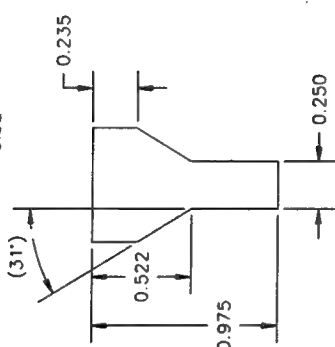
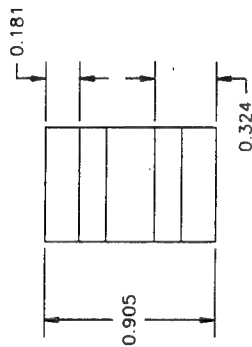
-3 Ring Detail



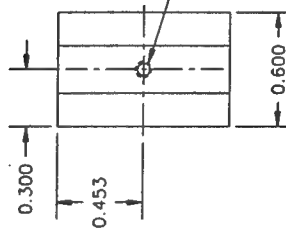
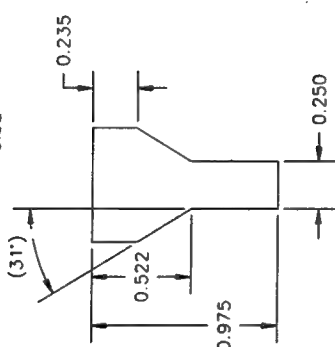
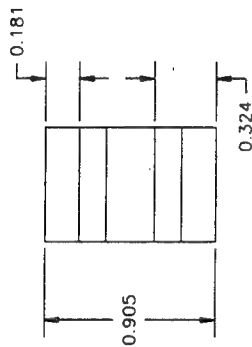
-3 Ring Detail



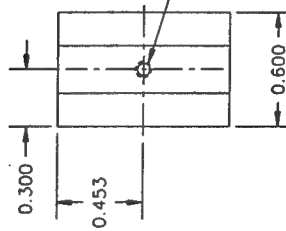
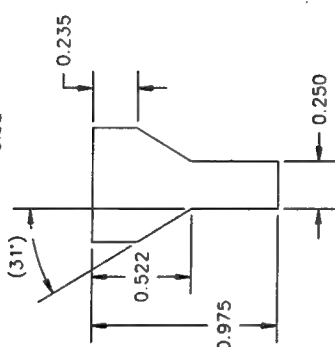
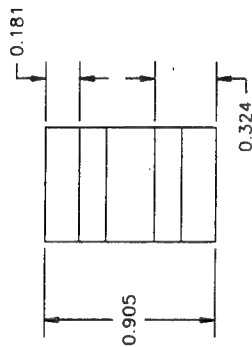
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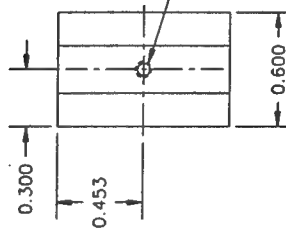
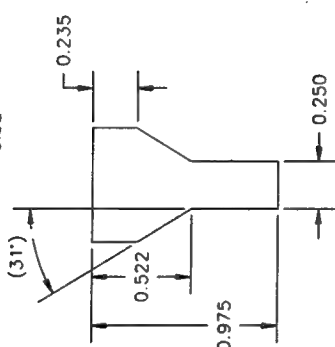
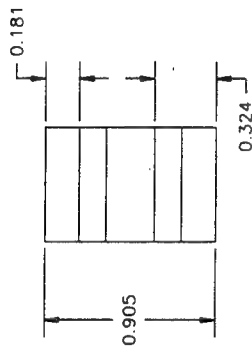
-3 Ring Detail



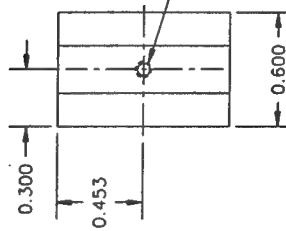
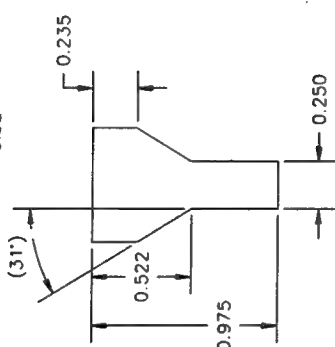
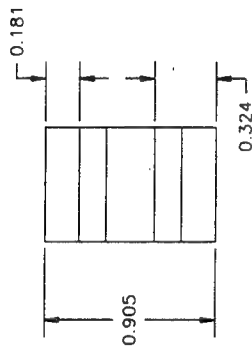
-3 Ring Detail



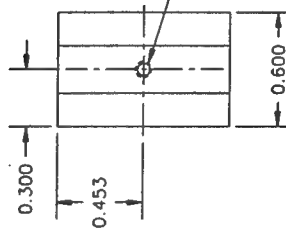
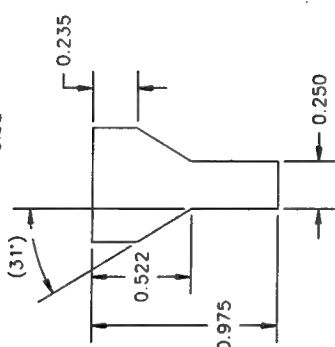
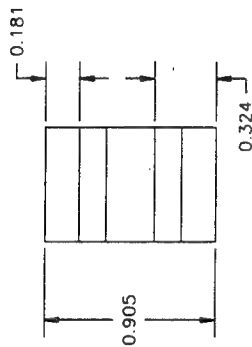
-3 Ring Detail



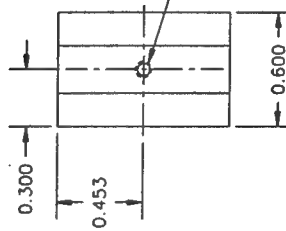
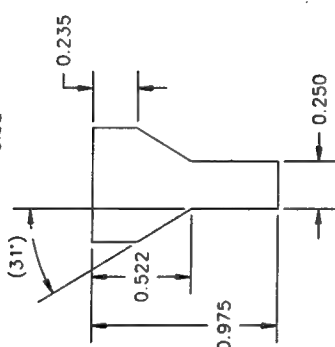
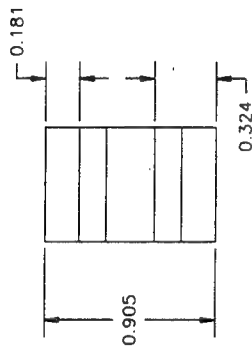
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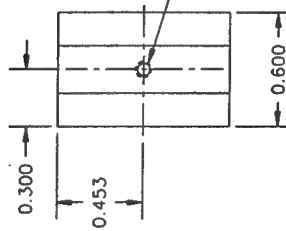
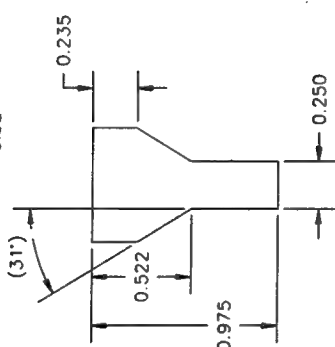
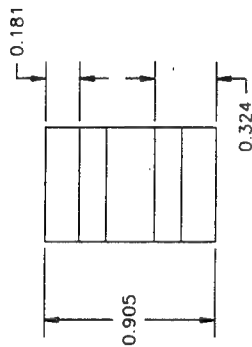
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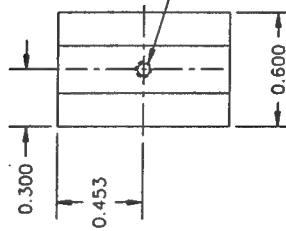
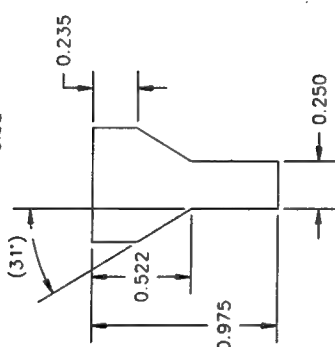
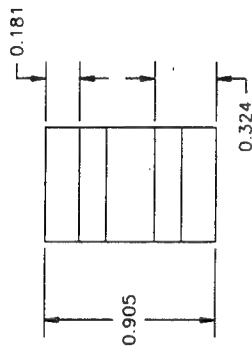
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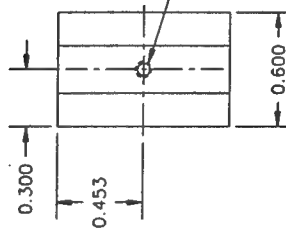
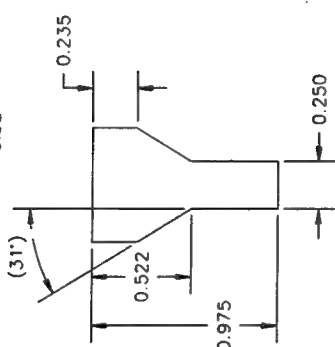
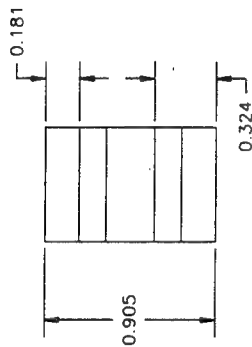
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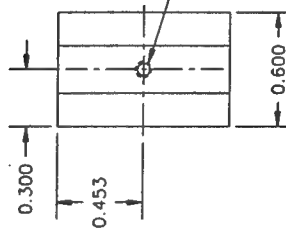
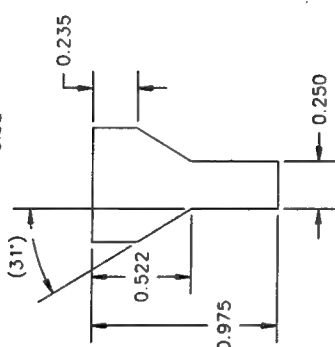
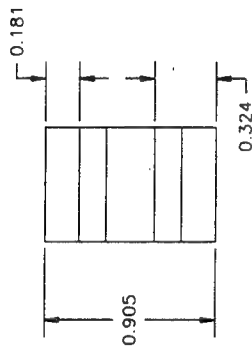
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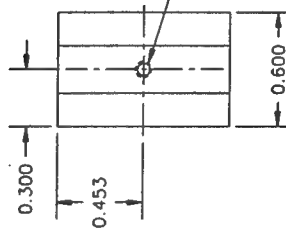
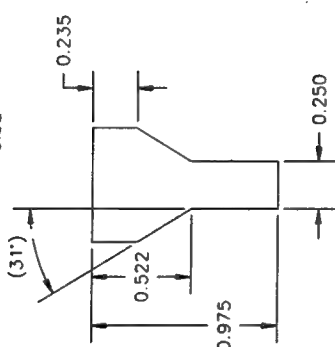
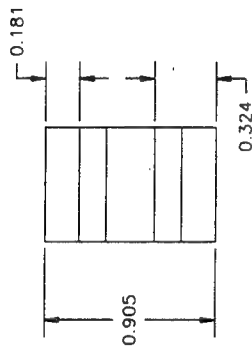
-3 Ring Detail



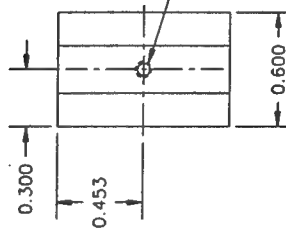
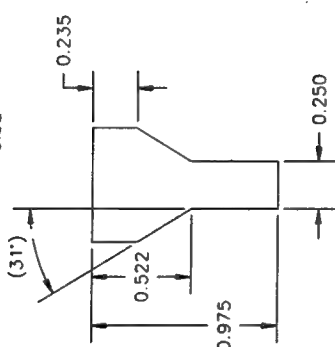
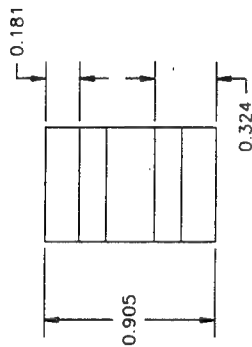
-3 Ring Detail



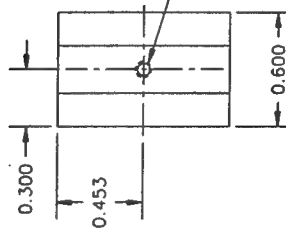
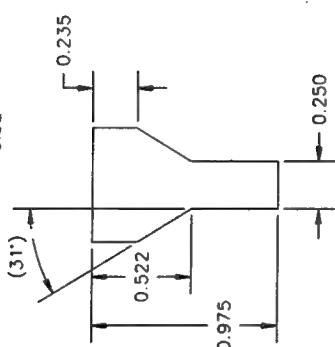
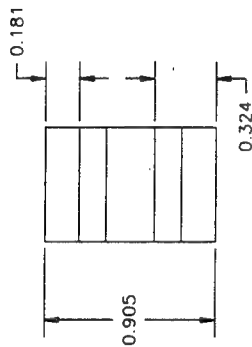
-3 Ring Detail



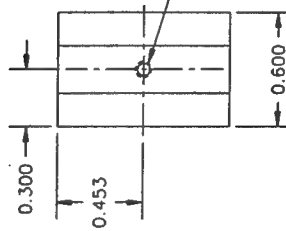
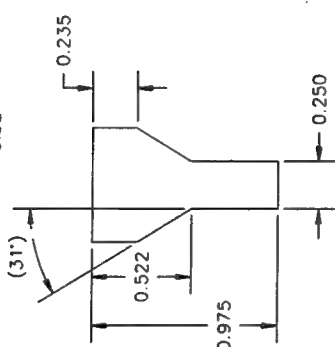
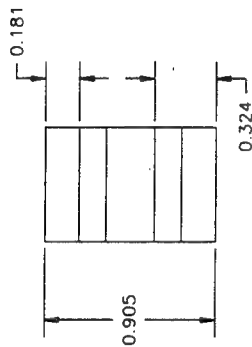
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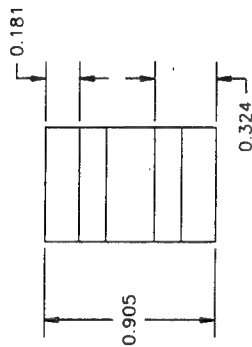
-3 Ring Detail

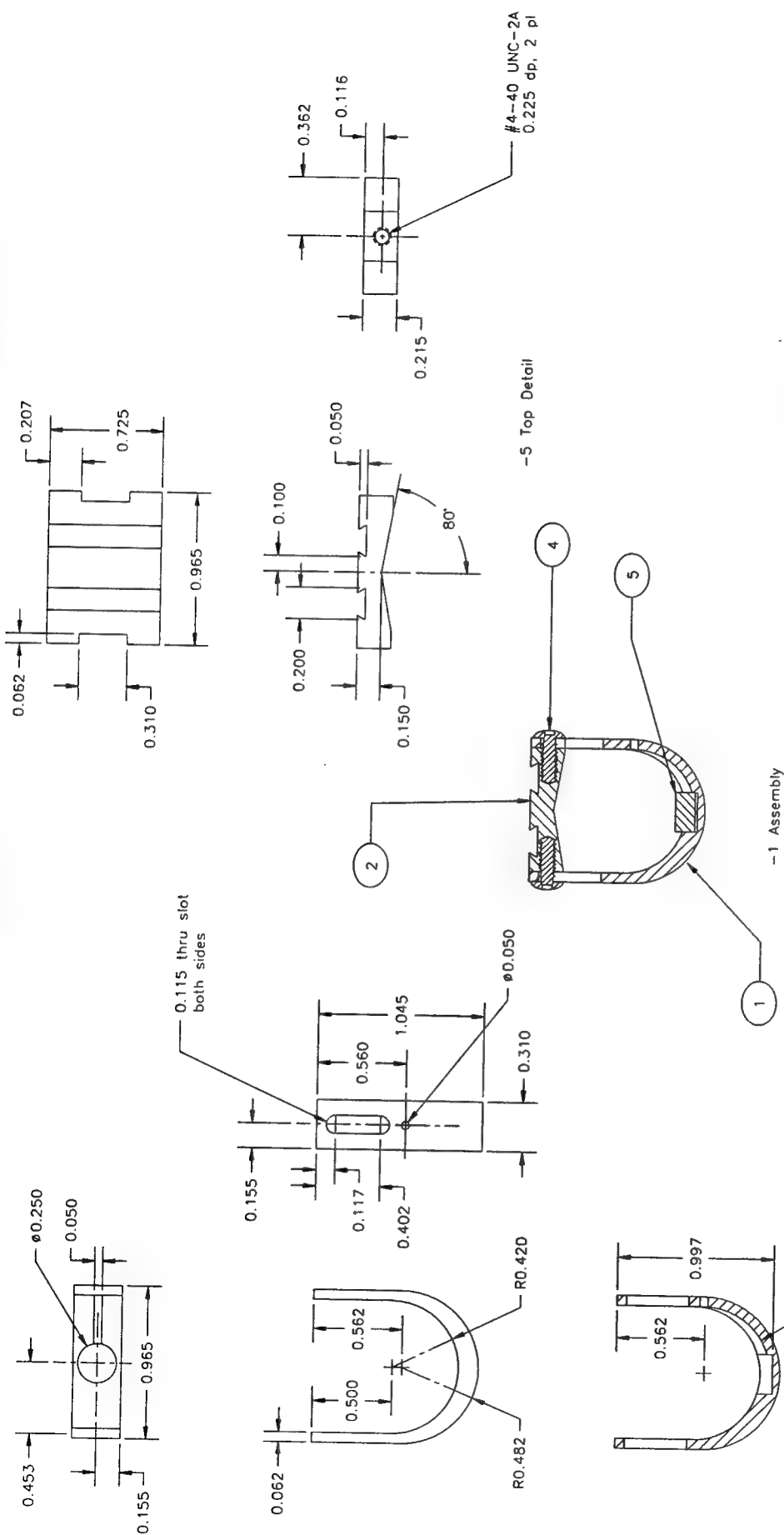


-3 Ring Detail



-3 Ring Detail





QTY	ITEM	PART NO.	DESCRIPTION	MAT'L/SPEC
1	5	ALD-MICRO	1/4D x 1/8, 10# Id cell	---
2	4	4C2SKBCY	1/4-40 x 1/4 Bln Soc Cap	SS
1	3	XXX	---	---
1	2	BE000266-5	Ring Top	Delrin
1	1	BE000266-3	Ring Base	Delrin
1	---	BE000266	RING ASSEMBLY	---

③  
②  
①

AL Design, Inc., 1411 Military Rd, Buffalo, NY 716-875-6240  
Fasteners of comparable spec's acceptable.  
ABABA Bolt Inc., El Cajon, CA (619) 440-1781

# PARTS LIST

tra

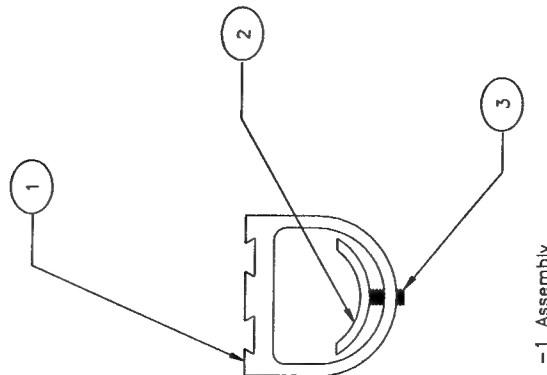
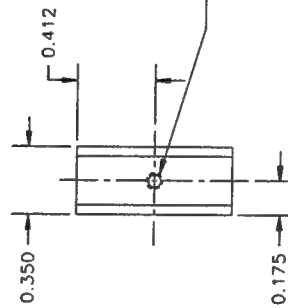
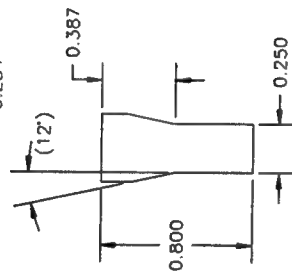
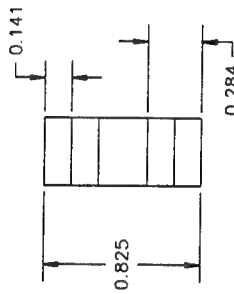
TITLE: Ring Mount - MIP; Exoskeleton

SCALE: 2:1	DATE: 22 Aug 95	No. BE000266
DRAWN BY: A. P. Hilton	RELEASE DATE: 17 Oct 95	
PROJECT: Actuator II	APPROVAL:	C
FILE NAME: BE00266.dwg		

NO.	REVISION	DATE	BY
3	length/width of top section, ring height & dia	17 Oct 95	APH
2	two piece adjustable, load cell mount	14 Sep 95	APH
1	height, clamp pos, load cell mnt, strain relief	12 Sep 95	APH

Unless otherwise specified:  
Dimensions are in inches  
Tolerances on angles  $\pm 0^\circ 30'$   
Decimals .XX  $\pm .03$ , .XXX  $\pm .005$

Rev D	Heat Treat: N/A
Mati: Delrin	



-5 Clamp Detail

-3 Ring Detail

② Fasteners of comparable spec's acceptable.  
① Small Parts Inc., Miami Lakes, FL 1-800-220-4242

QTY	ITEM	PART NO.	DESCRIPTION	MAT'L/SPEC
1	5	XXX	XXX	---
1	4	XXX	XXX	---
1	3	SSAS-256-3	#2-56 x 3/16 set screw	---
1	2	BE000269-5	Adjustment Clamp	---
1	1	BE000269-3	Ring	---
1	---	BE000269	RING ASSEMBLY	---
1	---	---	---	---

①②

# PARTS LIST

tra

TITLE: Ring Mount - DIP; Exoskeleton

SCALE: 2:1 DATE: 25 Aug 95 No. BE000269

DRAWN BY: A. P. Hilton RELEASE DATE: 25 Aug 95

PROJECT: Actuator II APPROVAL:

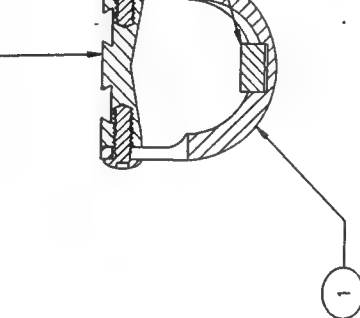
FILE NAME: BE000269.dwg C

Unless otherwise specified:  
Dimensions are in inches  
Tolerances on angles  $\pm 0^\circ 30'$   
Decimals .XX  $\pm 0.3$ , .XXX  $\pm .005$

Rev A

Mati: Delrin

Heat Treat:



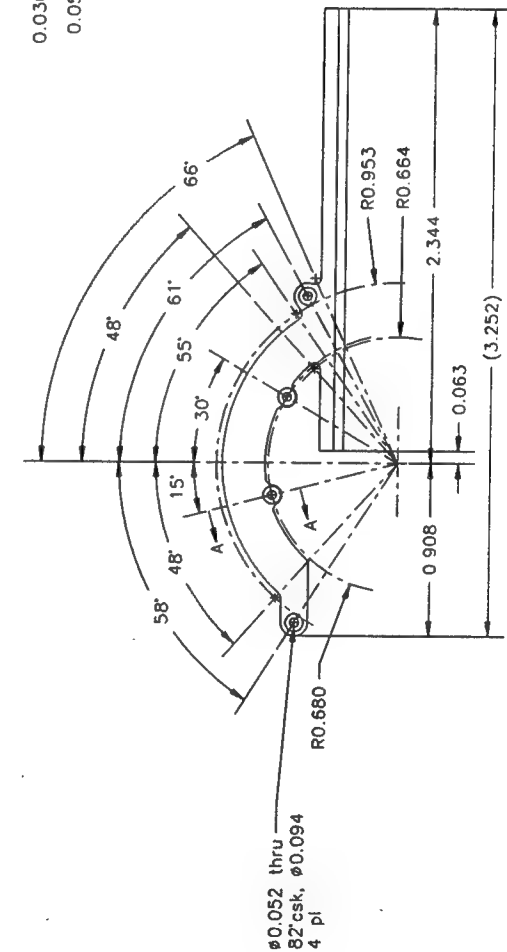
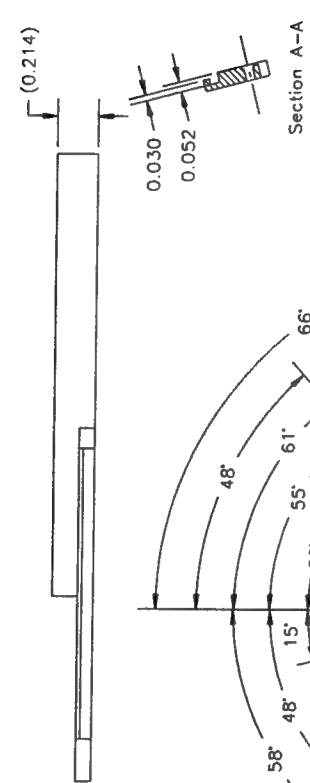
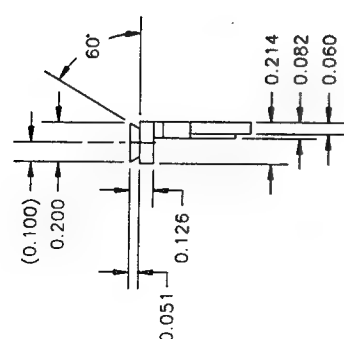
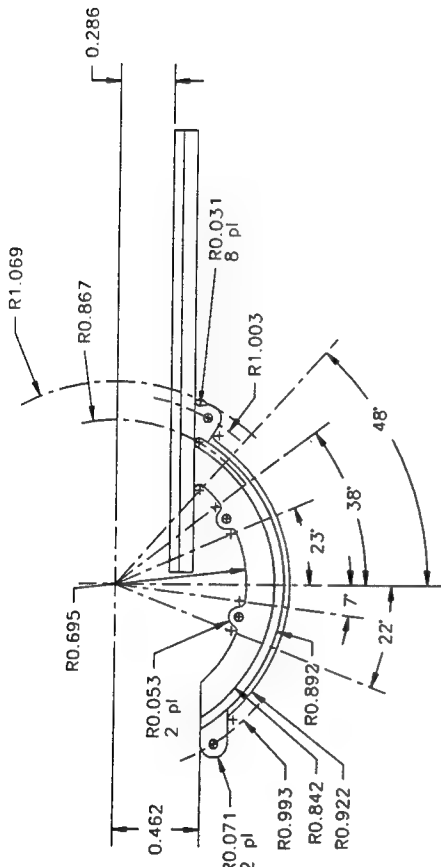
-1 Assembly

三

Unless otherwise specified:  
Dimensions are in inches  
Tolerances on angles  $\pm 0^\circ 30'$   
Decimals .XX  $\pm .03$ , .XXX  $\pm .005$

D	width and dia of ring	17 Oct 95	APH
C	two piece adjustable, load cell mount	14 Sep 95	APH
B	height, clamp pos, load cell mnt, strain relief	25 Aug 95	APH
NO.	REVISION	DATE	BY

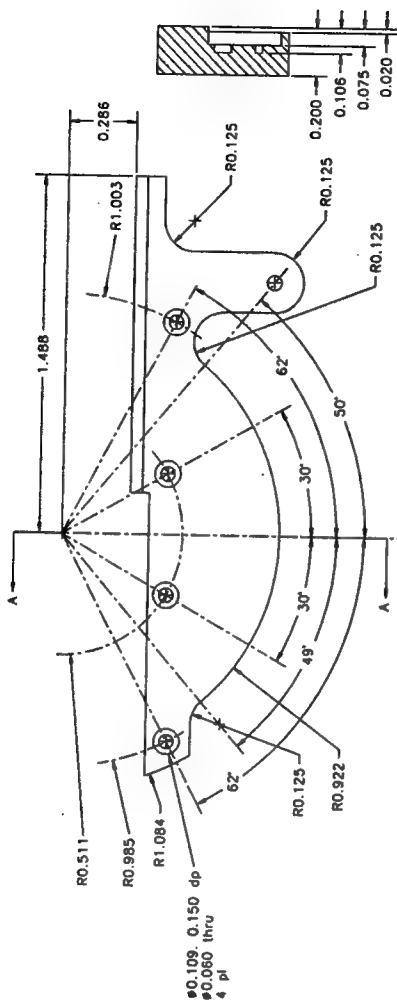
③ AL Design, Inc., 1411 Military Rd, Buffalo, NY 716-875-6240  
 ② Fasteners of comparable spec's acceptable.  
 ① ABABA Bolt Inc., El Cajon, CA (619) 440-1781



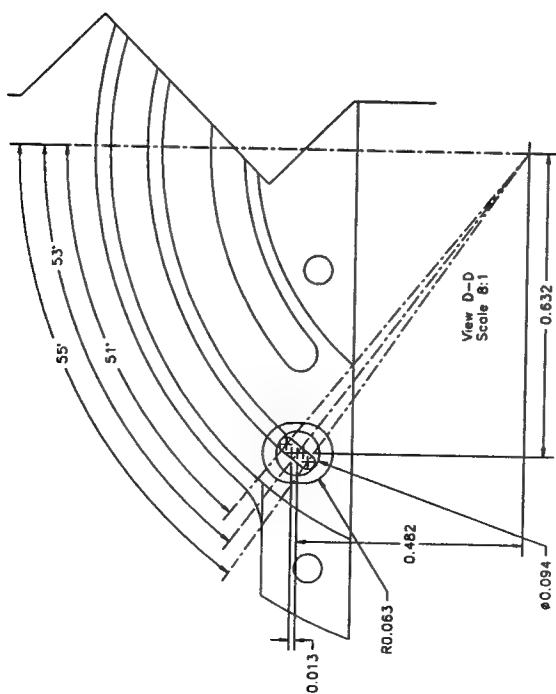
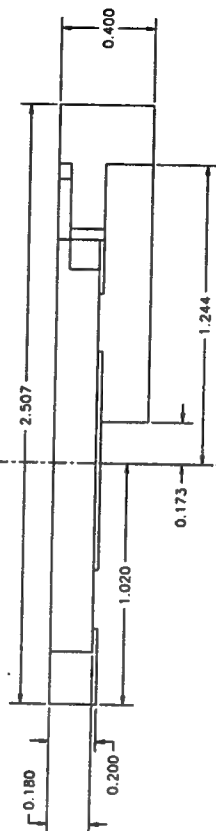
tra

TITLE: Base; SVJ (sliding virtual joint)		No. BE000270	
SCALE: 2:1	DATE: 31 Aug 95	RELEASE DATE: 6 Sep 95	
DRAWN BY: A. P. Hilton		PROJECT: Actuator II	
FILE NAME: BE00270.dwg		APPROVAL: C	

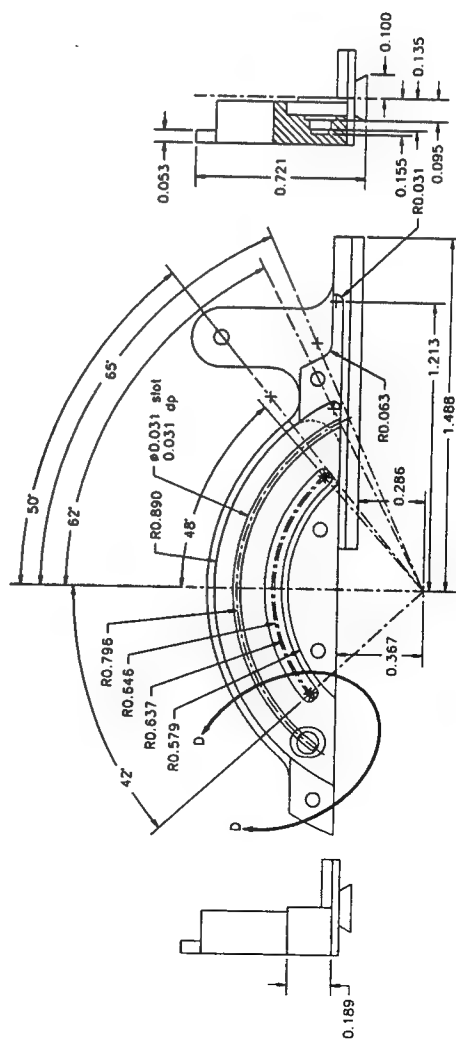
Unless otherwise specified: Dimensions are in inches Tolerances on angles ± 0° 30' Decimals .XX ± .03, .XXX ± .005		Rev A	
Motl: Delrin		Heat Treat:	



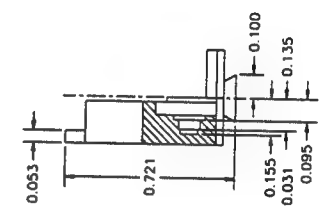
Section A-A



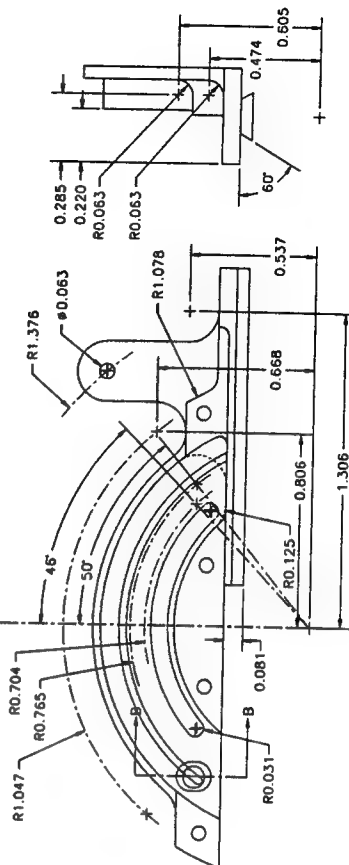
View D-D  
Scale 8:1



Supplemental View

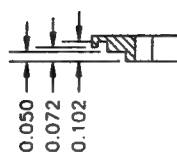
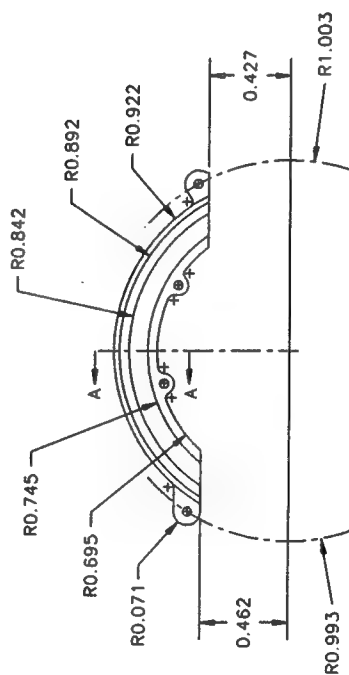
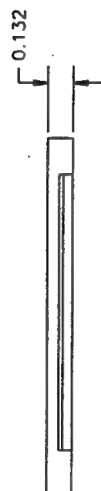
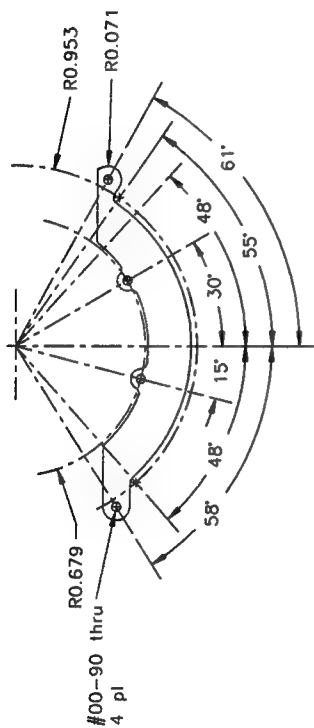


Section B-B



tr3

DESIGNED BY	DATE	SCALE	PROJECT	FILE NAME
Basej, SVJ (Sliding Virtual Joint)	4/1	1:1	31 Aug 95	BE000270
DESIGNED BY	DATE	SCALE	PROJECT	FILE NAME
Basej, SVJ (Sliding Virtual Joint)	4/1	1:1	31 Aug 95	BE000270
DESIGNED BY	DATE	SCALE	PROJECT	FILE NAME
Basej, SVJ (Sliding Virtual Joint)	4/1	1:1	31 Aug 95	BE000270
DESIGNED BY	DATE	SCALE	PROJECT	FILE NAME
Basej, SVJ (Sliding Virtual Joint)	4/1	1:1	31 Aug 95	BE000270
DESIGNED BY	DATE	SCALE	PROJECT	FILE NAME
Basej, SVJ (Sliding Virtual Joint)	4/1	1:1	31 Aug 95	BE000270



Section A-A

tra

TITLE: Clamp; SVJ (sliding virtual joint)

SCALE: 2:1 DATE: 31 Aug 95 No. BE000271

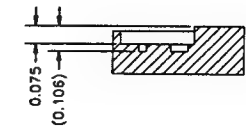
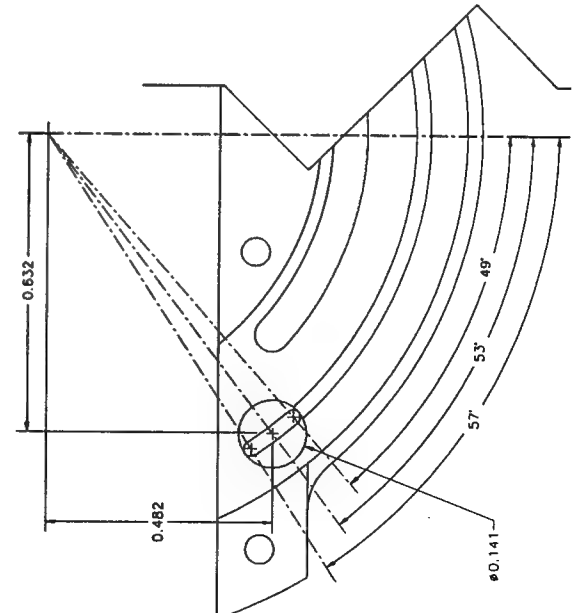
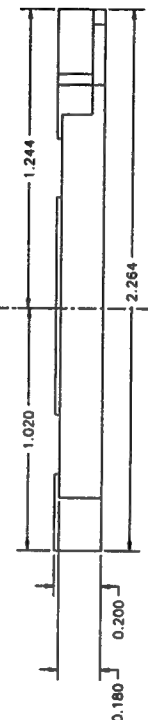
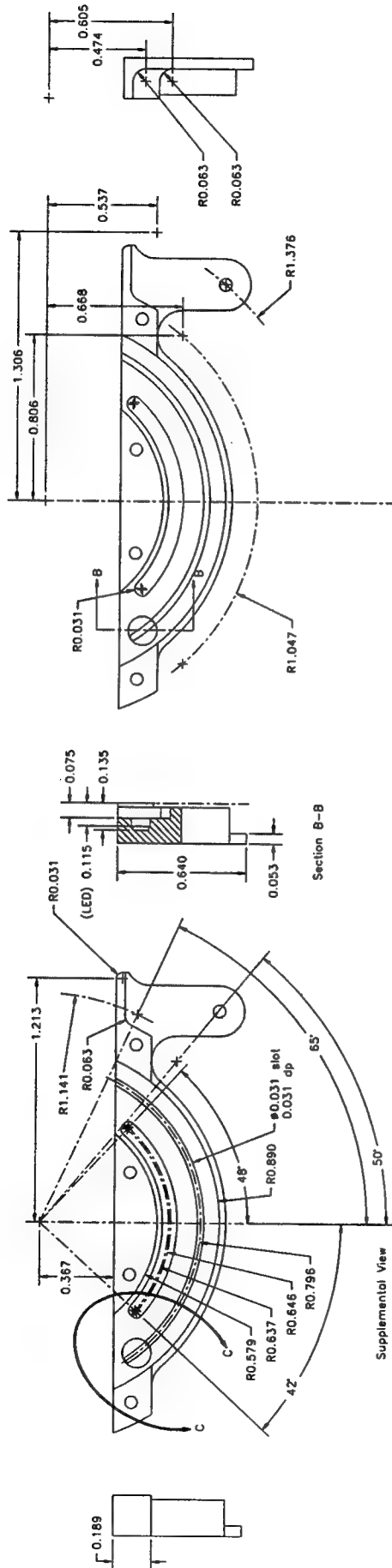
DRAWN BY: A. P. Hilton RELEASE DATE: 5 Sep 95

PROJECT: Actuator II APPROVAL:

FILE NAME: BE00271.dwg C

Unless otherwise specified:  
Dimensions are in inches  
Tolerances on angles  $\pm 0^\circ 30'$   
Decimals .XX  $\pm .03$ , .XXX  $\pm .005$

Rev A  
Matl: Delrin  
Heat Treat:

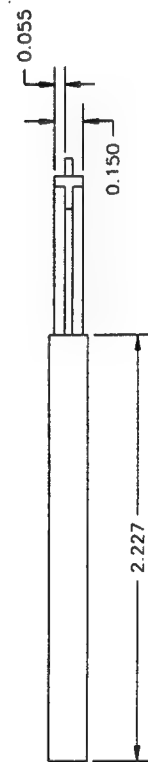
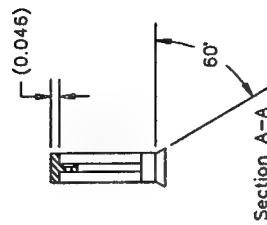
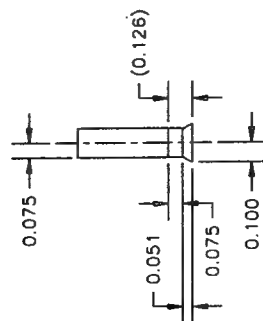
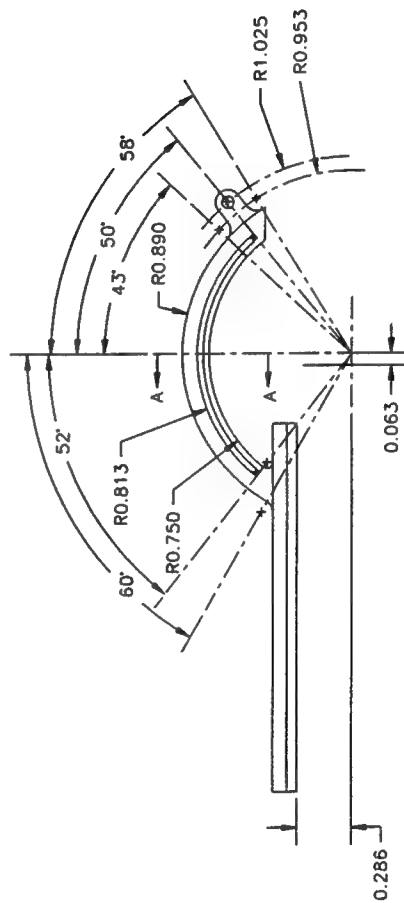
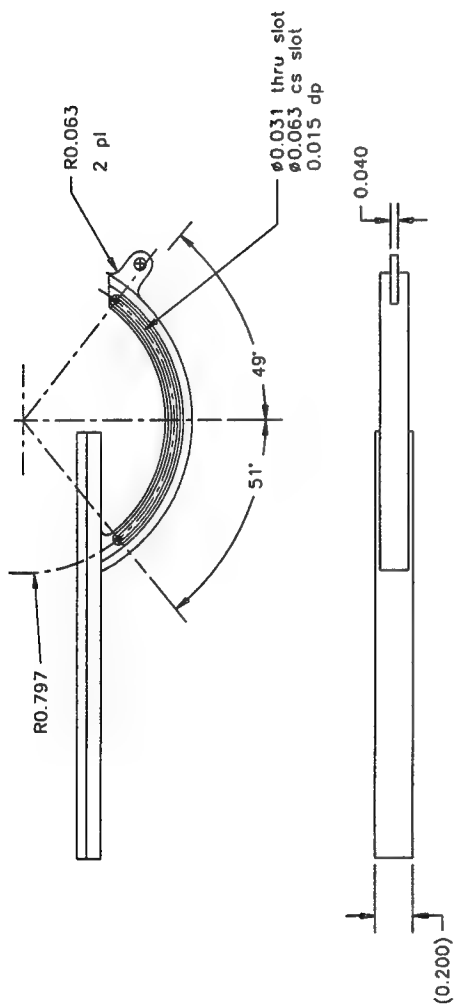


Section A-A

**tree**

Title: Clamp; SVJ Sliding Virtual Joint		Rev C	DATE: 31 Aug 95	Rev C
Scale: 4:1		Drawn By: A. P. Hilton	Release Date: 2 Dec 95	Rev C
Part Name: BE000271		Project: Actuator II	Approval:	DE
Unless otherwise specified		Dimensions are in inches & fractions	Dimensions are in mm & decimals	
Tolerances are as follows:		Fit: H7/g6	Fit: H7/g6	
Surfaces are to be finished to:		Surface Finish: 32	Surface Finish: 32	
Holes are to be drilled to:		Holes: 32	Holes: 32	
Threads are to be:		Threads: 32	Threads: 32	
Fasteners are to be:		Fasteners: 32	Fasteners: 32	





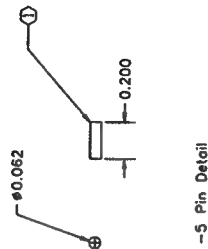
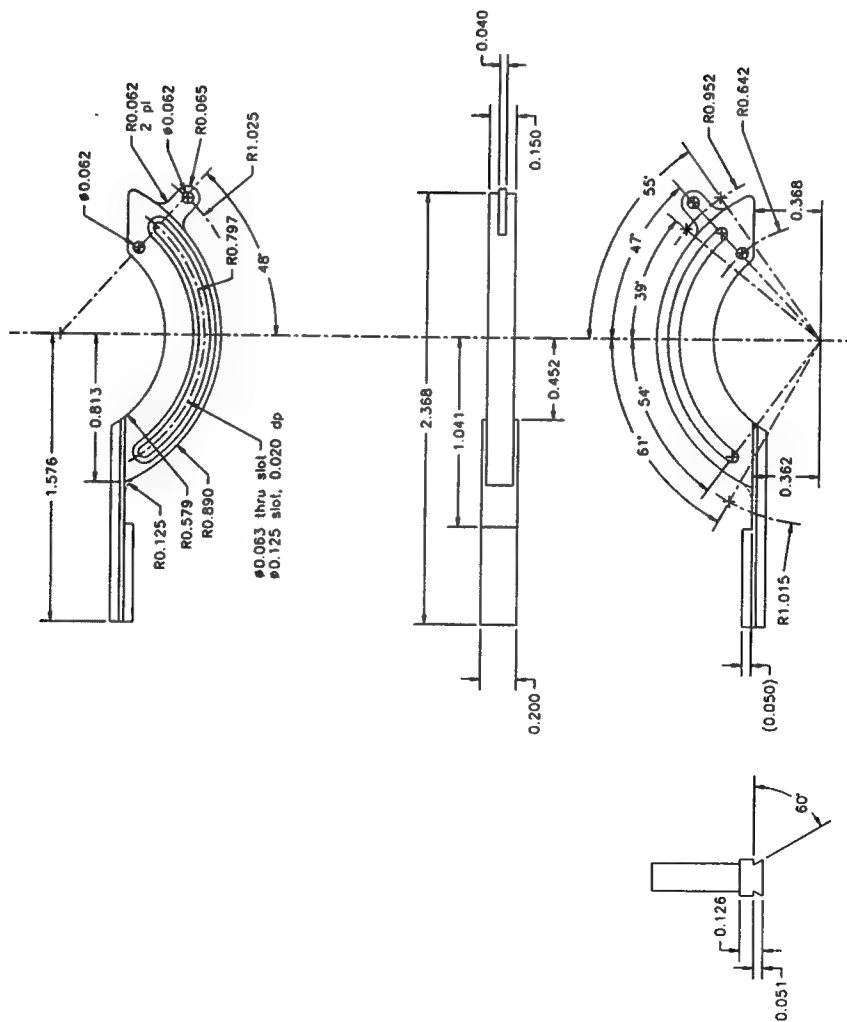
tra

Male Insert; SVJ

TITLE:	SCALE:	DATE:	No.
Male Insert; SVJ	2:1	6 Sep 95	BE000272
DRAWN BY:	PROJECT:	RELEASE DATE:	
A. P. Hilton	Actuator II	7 Sep 95	
FILE NAME:	APPROVAL:		
BE00272.dwg			C

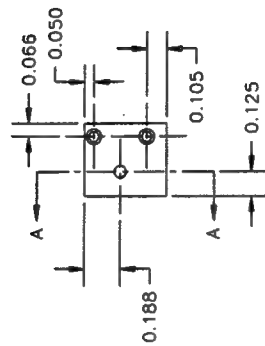
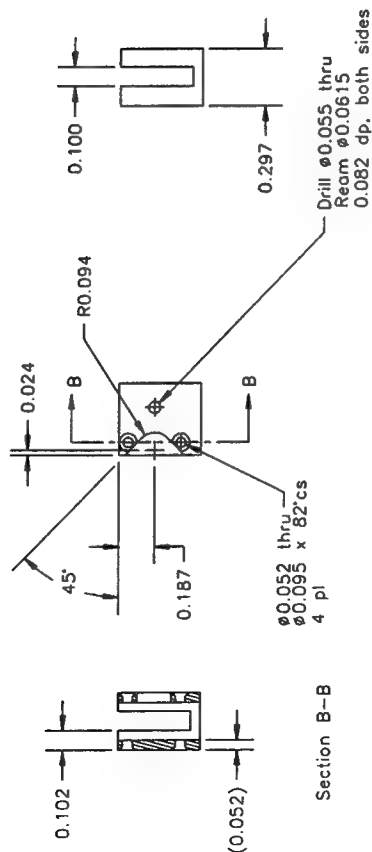
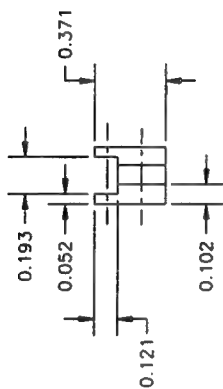
Unless otherwise specified:  
Dimensions are in inches  
Tolerances on angles ± 0° 30'  
Decimals .XX ± 0.3, .XXX ± 0.05  
Heat Treat:

Rev A  
Mati: Delrin  
Heat Treat:



① Use Part #: DWX-1-4, Small Parts, Inc., Miami Lakes, FL

trc		Male Insert; SVJ	
Unless otherwise specified Dimensions are in inches Tolerances on angles ± 0.30° Decimals 24 ± 0.005	Rev C	DATE: 6 Sep 95	REV: 0000272
Part: Alum 7075-T6	Drawn By: A. P. Hilton	DATE: 29 Sep 95	REV: 0000272
Project: Actuator II	Project: Actuator II	DATE: 29 Sep 95	REV: 0000272
Heat Treat:	Heat Treat:	DATE: 29 Sep 95	REV: 0000272
FILE NAME: E000272.dwg	FILE NAME: E000272.dwg	DATE: 29 Sep 95	REV: 0000272
		APPROVAL:	D



Section A-A

Section B-B

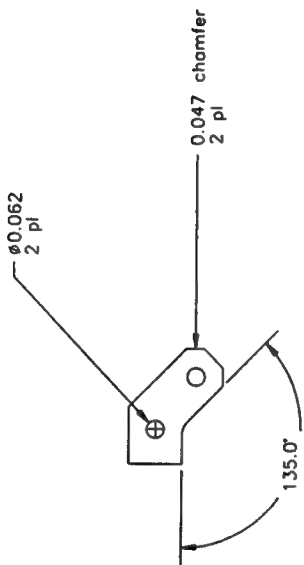
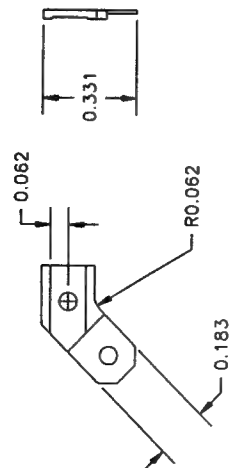
1ra

TITLE: U-Clip; Motor Mount

SCALE: 2:1	DATE: 22 Sep 95	No. BE000273
DRAWN BY: A. P. Hilton	RELEASE DATE: 3 Oct 95	
PROJECT: Actuator II	APPROVAL:	C
FILE NAME: BE00273.dwg		

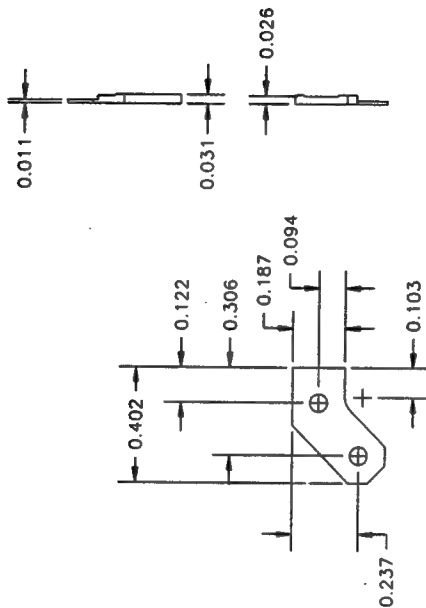
Unless otherwise specified:  
Dimensions are in inches  
Tolerances on angles  $\pm 0^\circ 30'$   
Decimals .XX  $\pm .03$ , .XXX  $\pm .005$

Rev A	Matl: 2011-TB Alum
Heat Treat:	

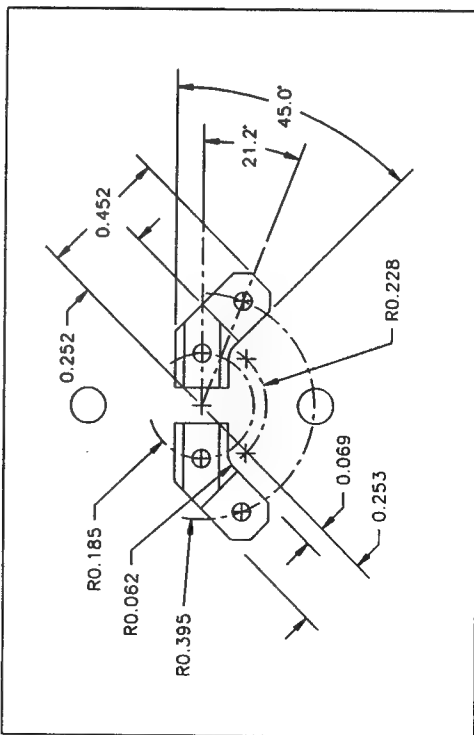


-3 Left Side

229



-5 Right Side

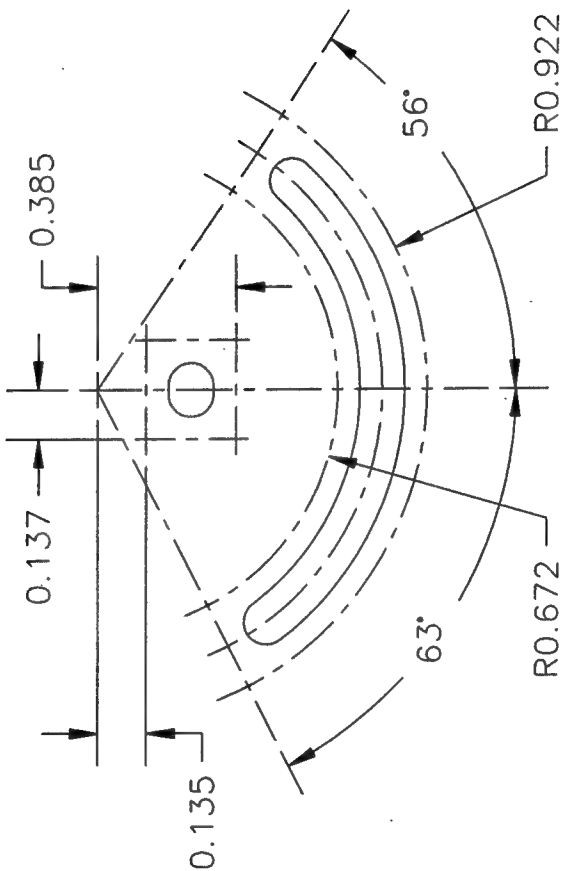


trc

TITLE: Ribbon Clip		No. BE000274	
SCALE: 3:1	DATE: 25 Sep 95	RELEASE DATE: 28 Sep 95	
DRAWN BY: A. P. Hilton		APPROVAL:	
PROJECT: Actuator II		C	
FILE NAME: BE00274.dwg			

Unless otherwise specified:  
 Dimensions are in inches  
 Tolerances on angles ± 0° 30'  
 Decimals: XX ± 0.3, XXX ± .001  
 Heat Treat:

Rev A  
 Matl: 0031 SS shin  
 Heat Treat:



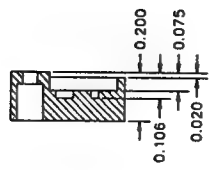
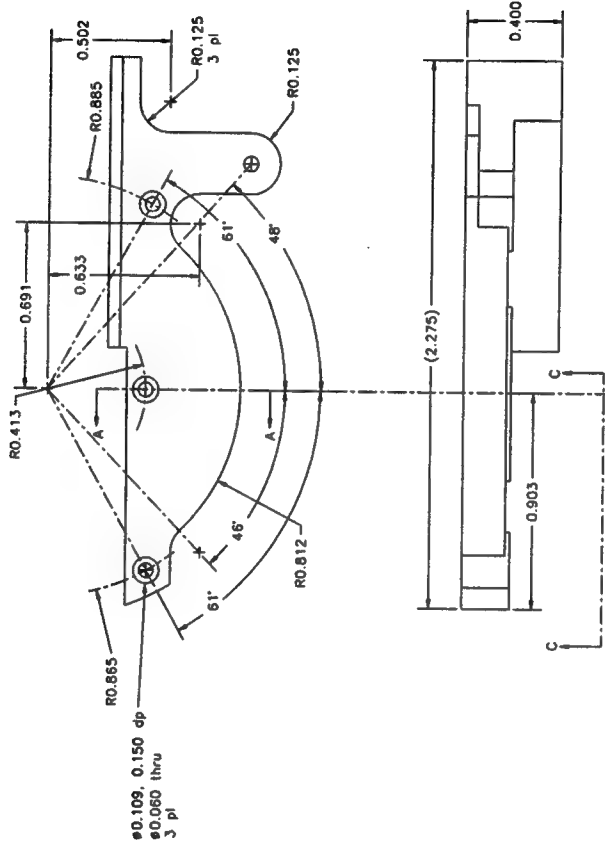
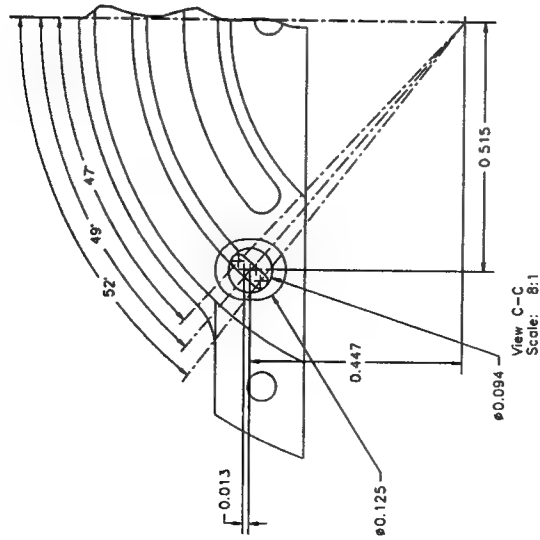
Use 0.125 end mill

tra

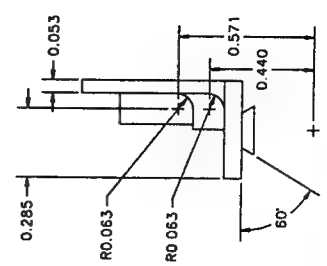
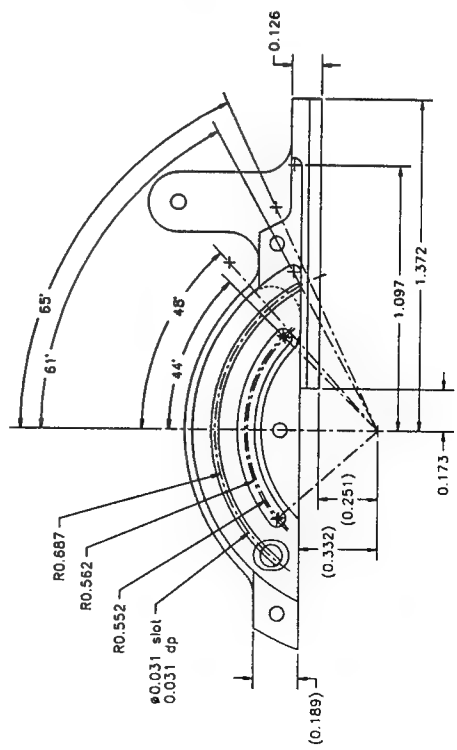
Polaroid Film Sections; Angle Sensor		
TITLE:		
SCALE: 2:1	DATE: 2 Oct 95	No. BE000276
DRAWN BY: A. P. Hilton		RELEASE DATE: 2 Oct 95
PROJECT: Actuator II		APPROVAL:  A
FILE NAME: be00276.dwg		

Unless otherwise specified:  
 Dimensions are in inches  
 Tolerances on angles  $\pm 0^\circ 30'$   
 Decimals .XX  $\pm .03$ , .XXX  $\pm .005$

Rev A  
 Matl:  
 Heat Treat:



Section A-A



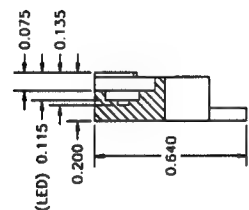
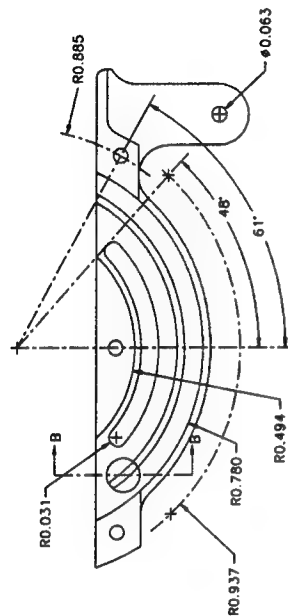
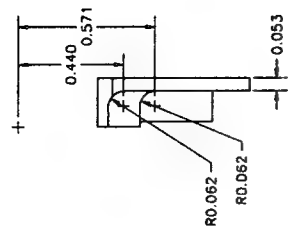
Section B-B

Supplemental View

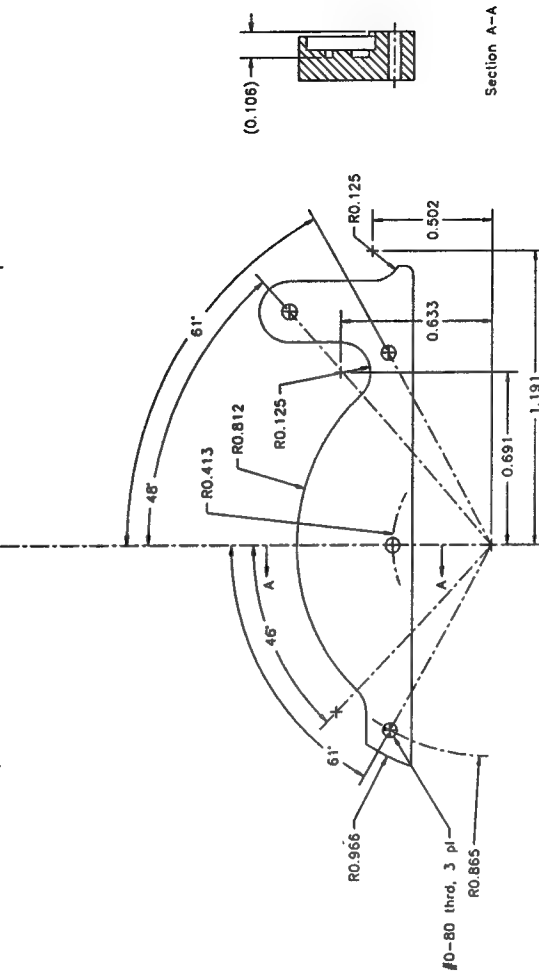
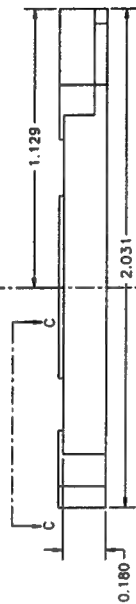
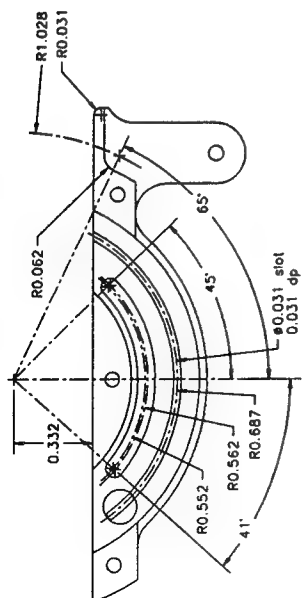
SVJ Base; DIP

DATE: 4-1	DATE: 5 Oct 95	REV: BE000277
DRAWN BY: A. P. Hilton	DESIGNED BY: S. B. C. 95	APPROVED: DE
PROJECT: Actuator II	FILE NAME: BE00277.dwg	

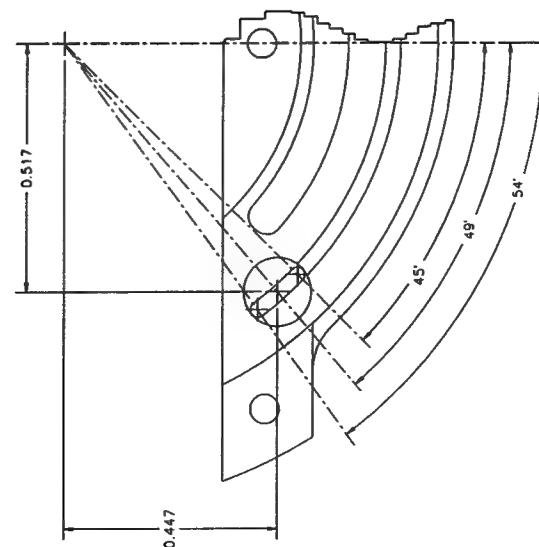
Unless otherwise specified  
Tolerances are in inches  
Decimals .XX ± .005  
Fractions 1/16 ± .005



Section B-B



Section A-A

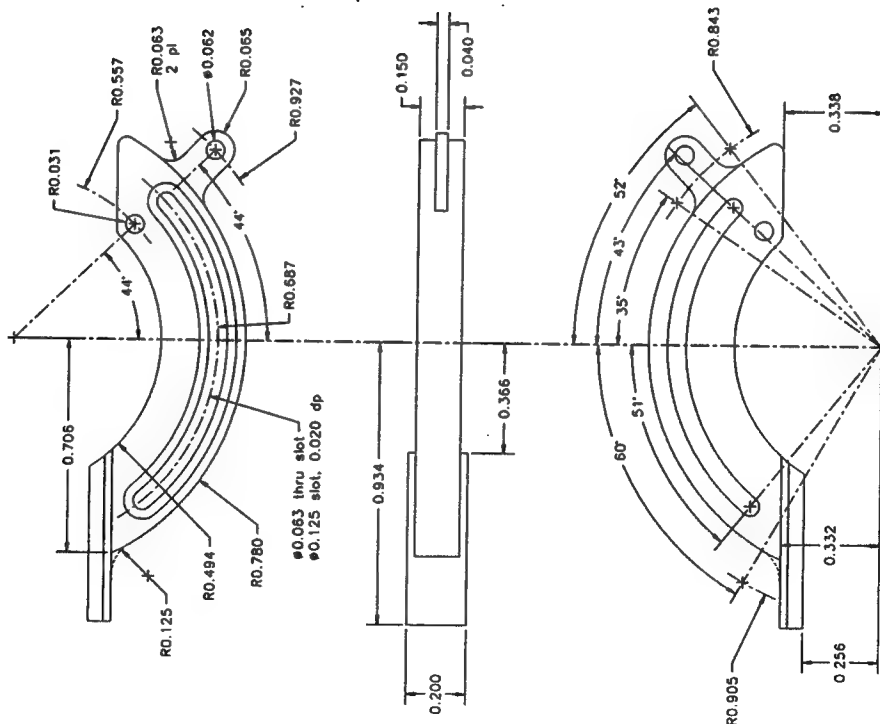


View C-C  
Scale B:1

tr3

FILE: SVJ Clamp; DIP

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON ANGLES ± 0.30° DECIMALS .XX ± .02 .XXX ± .005 HEAT TREAT	Rev A	DATE: 6 Oct 95	FILE NAME: BE00278.dwg
DRWN BY: A. P. Hilton	Rev A	DATE: 6 Oct 95	FILE NAME: BE00278.dwg
PROJEN: Actuator II	Rev A	DATE: 6 Oct 95	FILE NAME: BE00278.dwg
APPROVAL	Rev A	DATE: 6 Oct 95	FILE NAME: BE00278.dwg

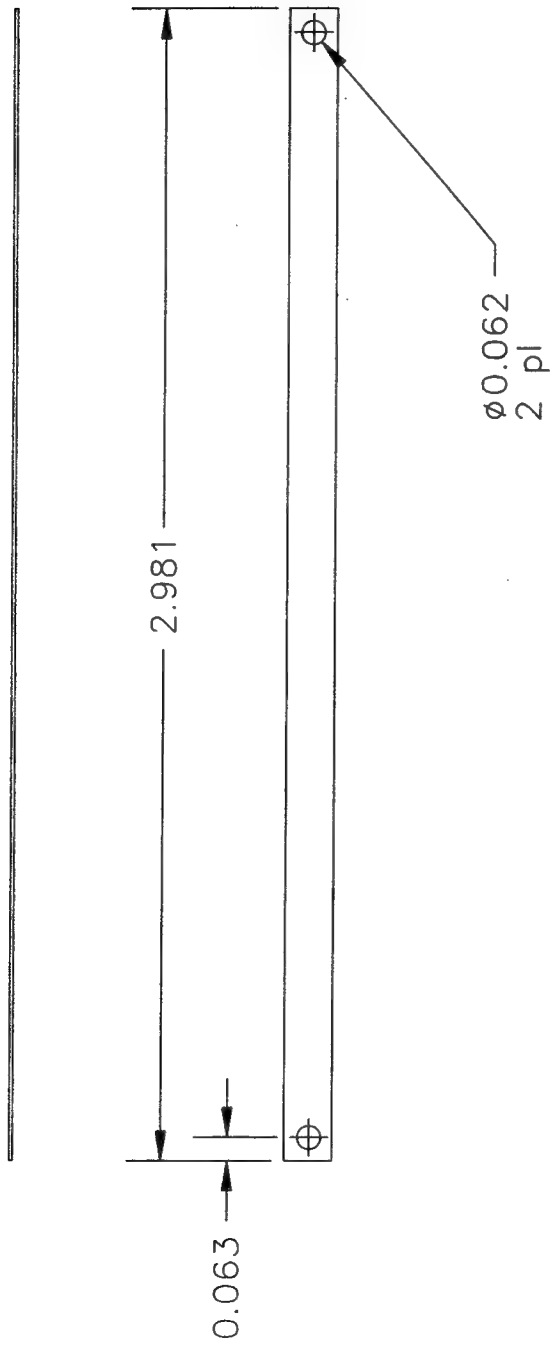


-3 Insert Detail

trc

Title: SVJ Male Insert, DIP		Rev A	Rev A	Rev A	Rev A
Scale: 5:1	Date: 6 Oct 95	Drawn by: A. P. Hilton	Project: 7075-16	File Name: BE00279.dwg	DE
Part No: BE000279		Project: 7075-16		Approval	
Tolerances are in inches		Tolerances are in inches		Tolerances are in inches	
Decimals: XX.XX		Decimals: XX.XX		Decimals: XX.XX	
Holes: 2X 1.00		Holes: 2X 1.00		Holes: 2X 1.00	
Holes: 2X 1.00		Holes: 2X 1.00		Holes: 2X 1.00	



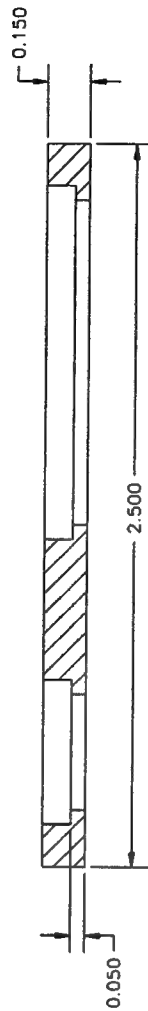
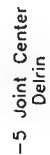
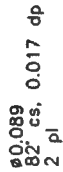


1 Use Starrett thickness gage gaps (0.009 x 0.125 x 6)  
as stock.

tra

TITLE: RIBBON-MIP; LINEAR MOTOR			
SCALE: 2:1	DATE: 6 Oct 95	No. BE000280	
DRAWN BY: A. P. Hilton		RELEASE DATE: 6 Oct 95	
PROJECT: Actuator II		APPROVAL:	
FILE NAME: be00280.dwg		A	

Unless otherwise specified: Dimensions are in inches	Rev A
Tolerances on angles ± 0° 30'	Mati:
Decimals .XX ± .03, .XXX ± .005	Heat Treat:

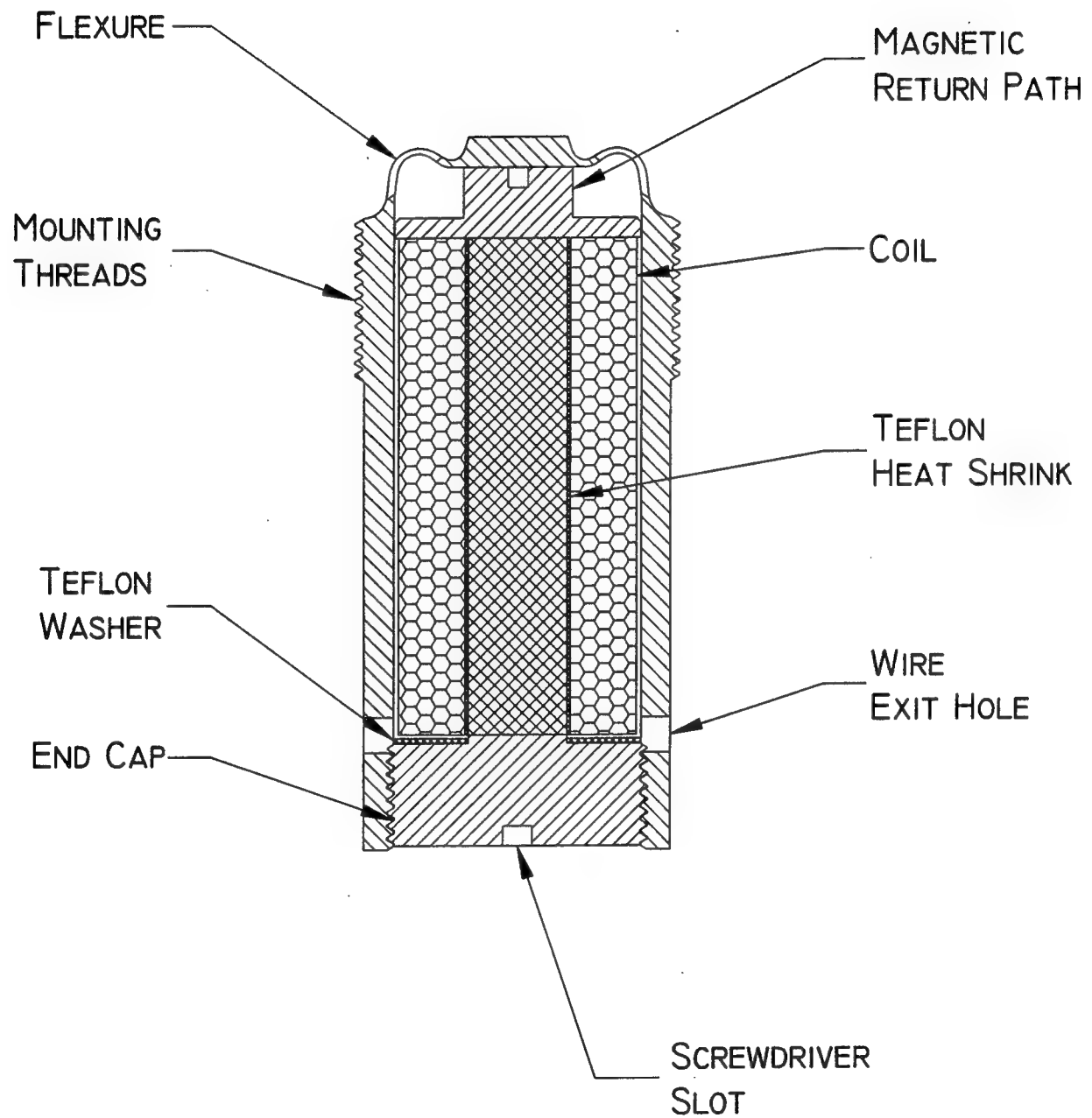


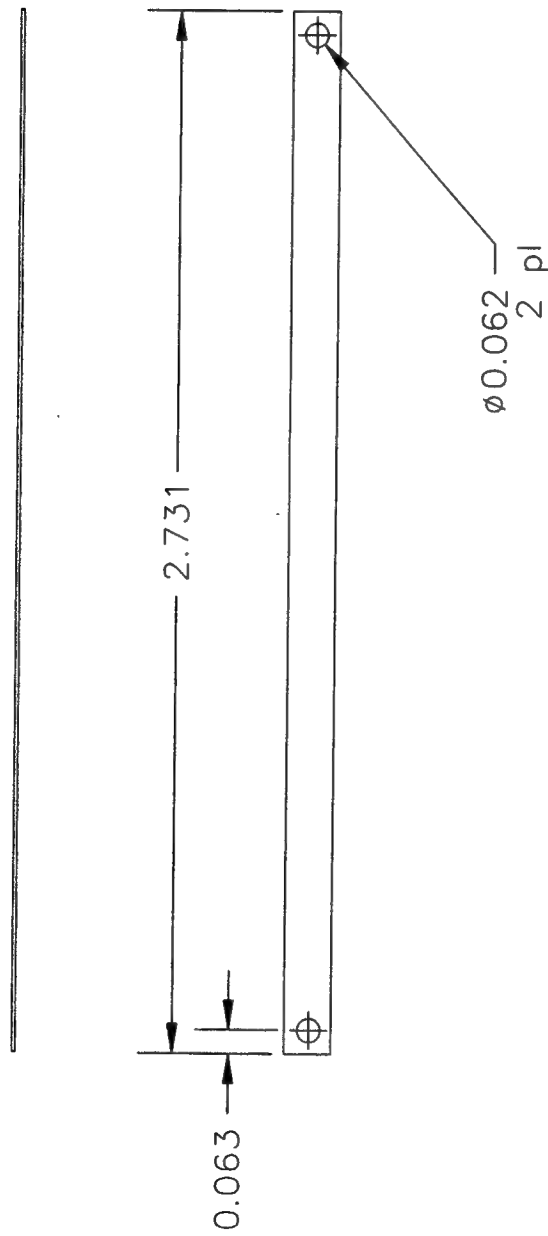
-3 PIP Joint Alum

10

Unless otherwise specified: Dimensions are in inches Tolerances on angles $\pm 0^{\circ} 30'$ Decimals .XX $\pm .03$ , .XXX $\pm .005$	Rev A	TITLE: PIP JOINT		
	Matl: (noted)	SCALE: 3:1	DATE: 11 Oct 95	No. BE000281
	Heat Treat:	DRAWN BY: A. P. Hilton	RELEASE DATE: 12 Oct 95	
		PROJECT: Actuator II	APPROVAL:	
		FILE NAME: BE00281.dwg		C

# MOTIVE CELL

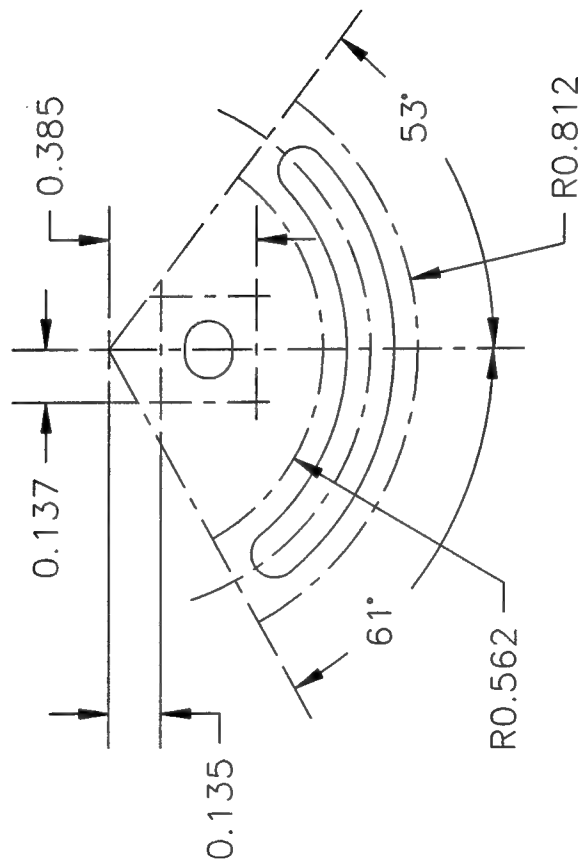




1 Use Starrett thickness gage gaps (0.009 x 0.125 x 6) as stock.

tra

TITLE: RIBBON-DIP; LINEAR MOTOR		No. BE000282	
SCALE: 2:1	DATE: 13 Oct 95	RELEASE DATE: 13 Oct 95	
DRAWN BY: A. P. Hilton		PROJECT: Actuator II	
Matl: Heat Treat:		APPROVAL: A	
FILE NAME: be00282.dwg			

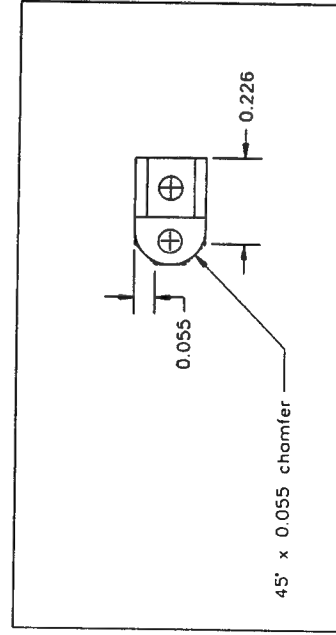
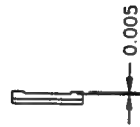
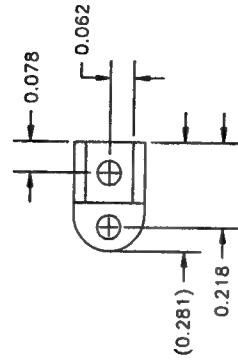
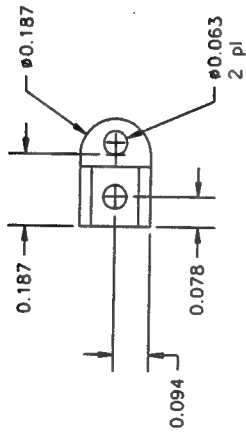
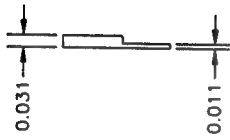


Use 0.125 end mill

1ra

TITLE: Polaroid Film Sections; DIP			
SCALE: 2:1	DATE: 13 Oct 95	No. BE000283	RELEASE DATE: 13 Oct 95
DRAWN BY: A. P. Hilton		PROJECT: Actuator II	
FILE NAME: be000283.dwg		APPROVAL: A	

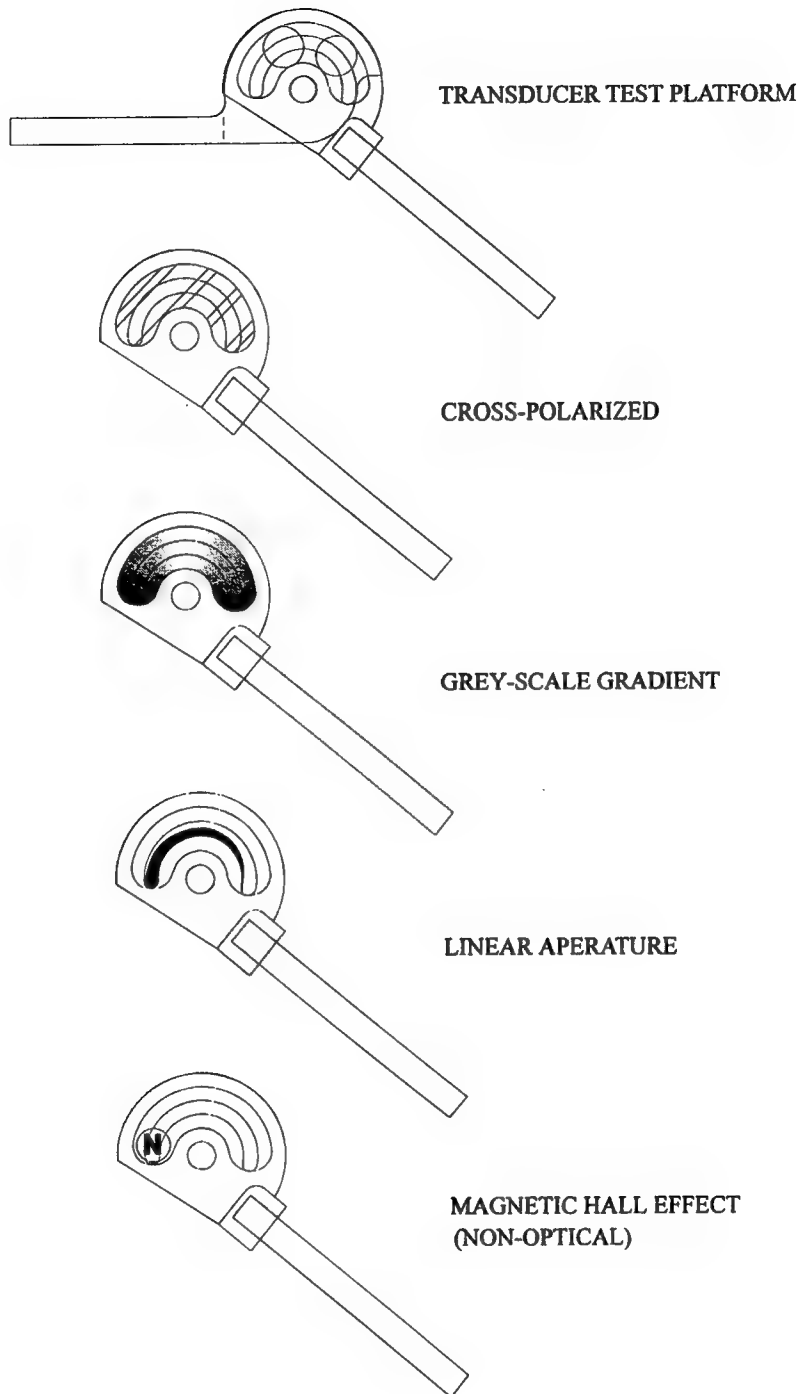
Unless otherwise specified: Dimensions are in inches	Rev A
Tolerances on angles $\pm 0^\circ 30'$	Matl: Heat Treat:
Decimals .XX $\pm .03$ , .XXX $\pm .005$	



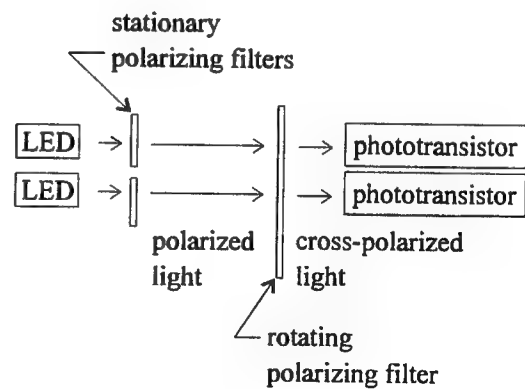
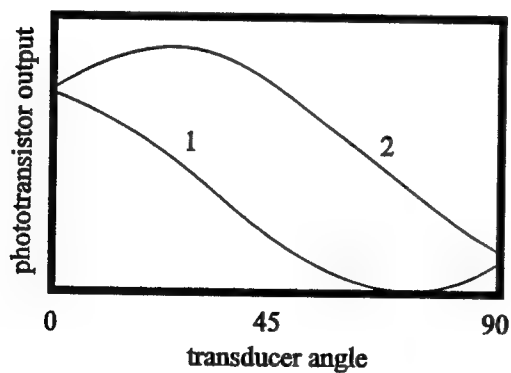
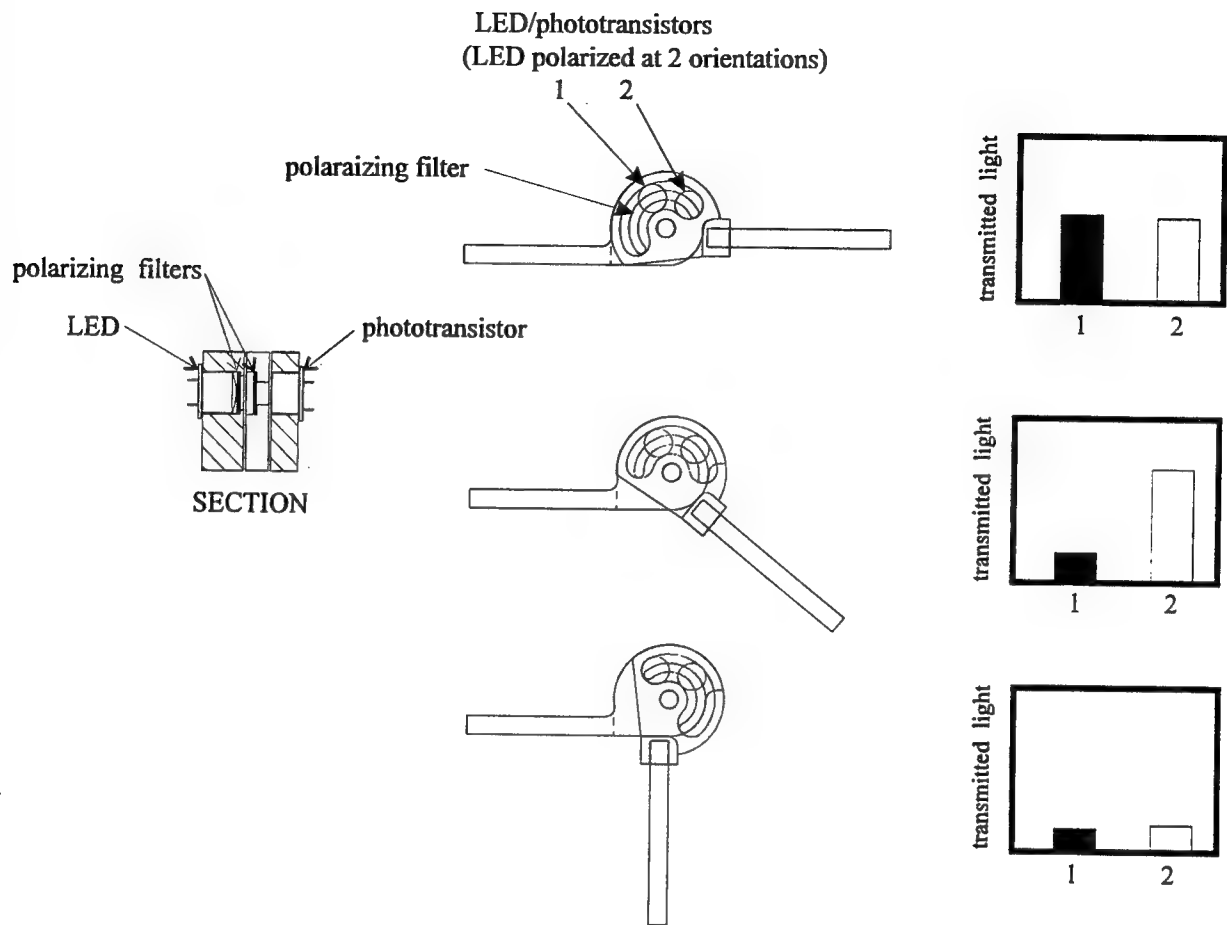
172

TITLE: Ribbon Clip			
SCALE: 4:1	DATE: 25 Sep 95	No. BE000274	
Rev C		DRAWN BY: A. P. Hilton	RELEASE DATE: 24 Oct 95
Matl: 0.031 SS shim		PROJECT: Actuator II	APPROVAL: C
Heat Treat:		FILE NAME: BE00274c.dwg	

Unless otherwise specified:  
 Dimensions are in inches  
 Tolerances on angles ± 0° 30'  
 Decimals .XX ± .03, .XXX ± .001



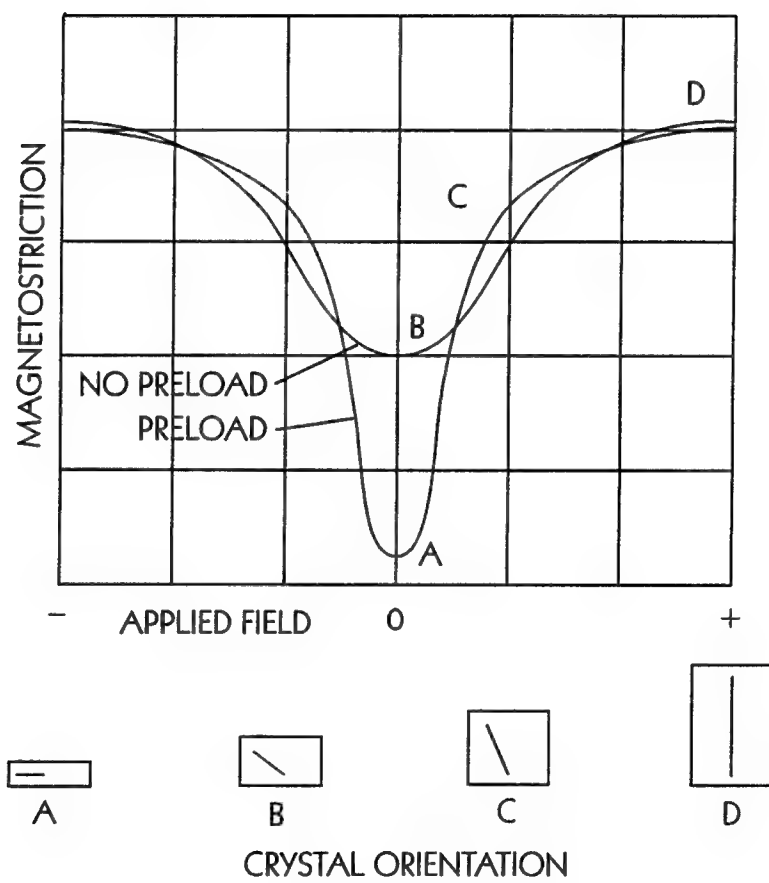
## JOINT DISPLACEMENT TRANSDUCER OPTIONS

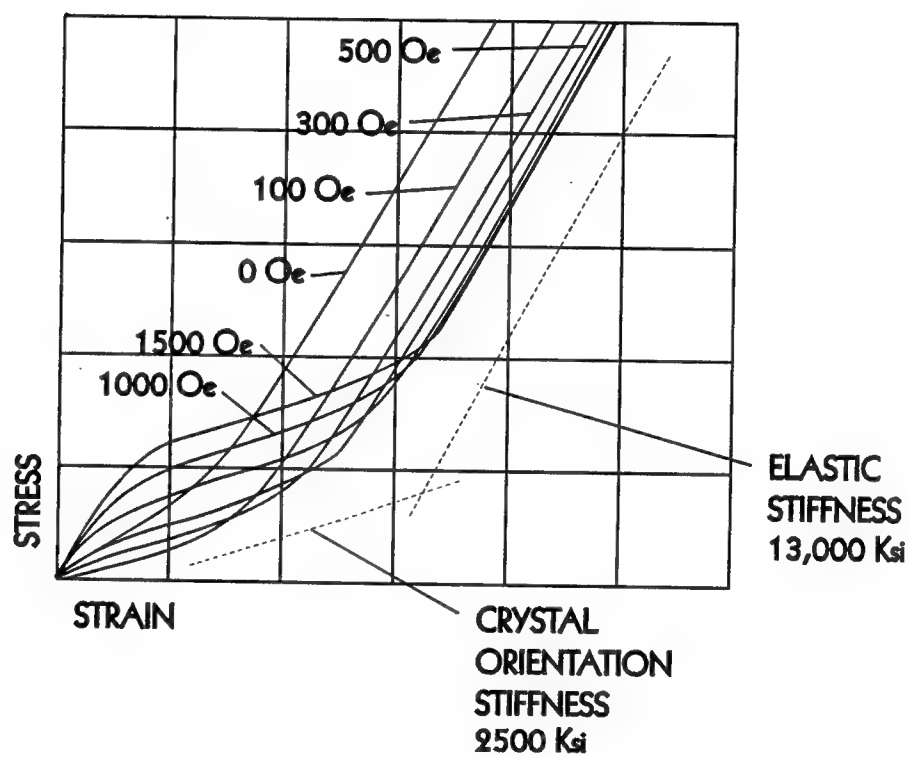


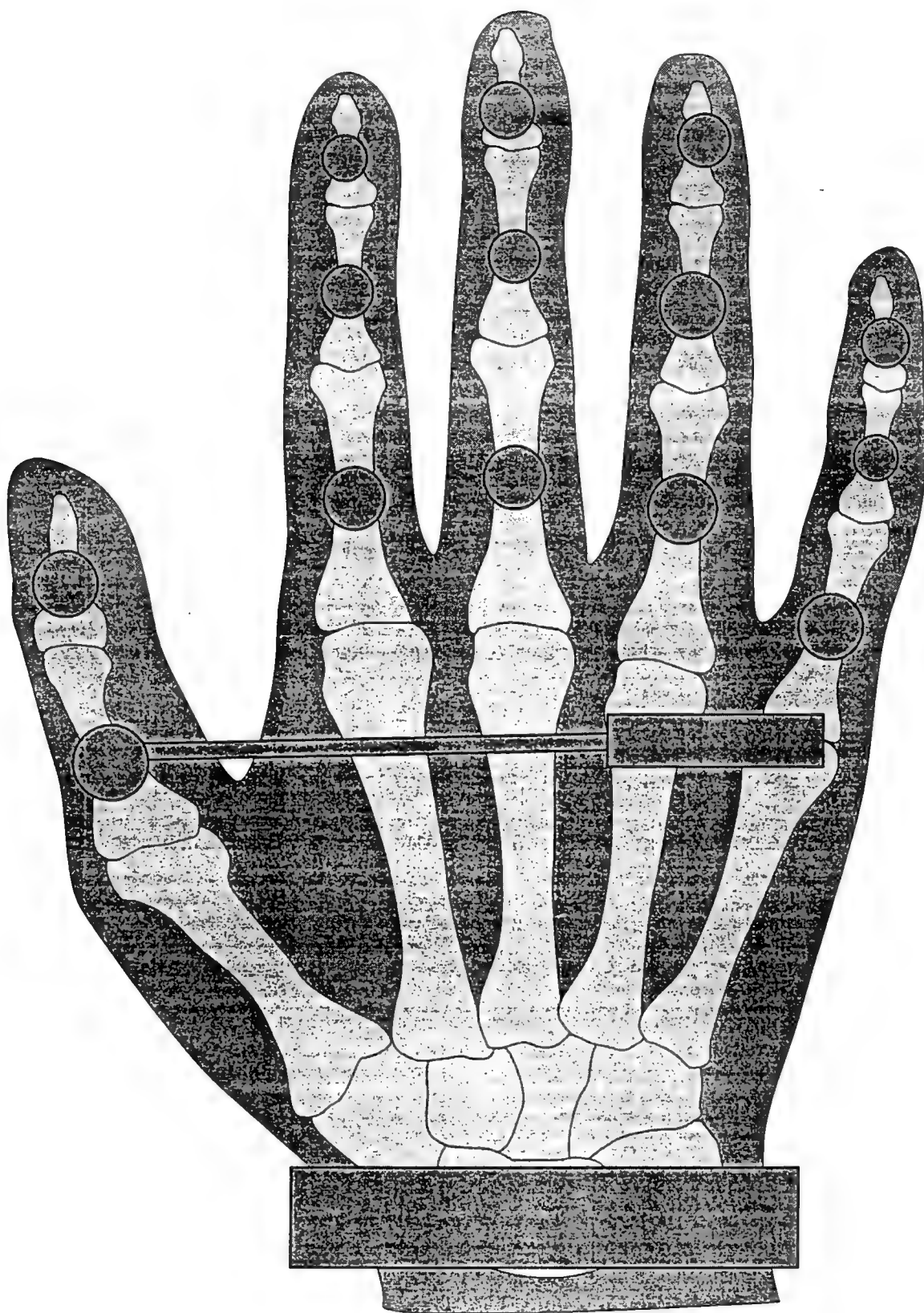
schematic

# JOINT DISPLACEMENT TRANSDUCER TEST PLATFORM POLARIZED LIGHT CONFIGURATION





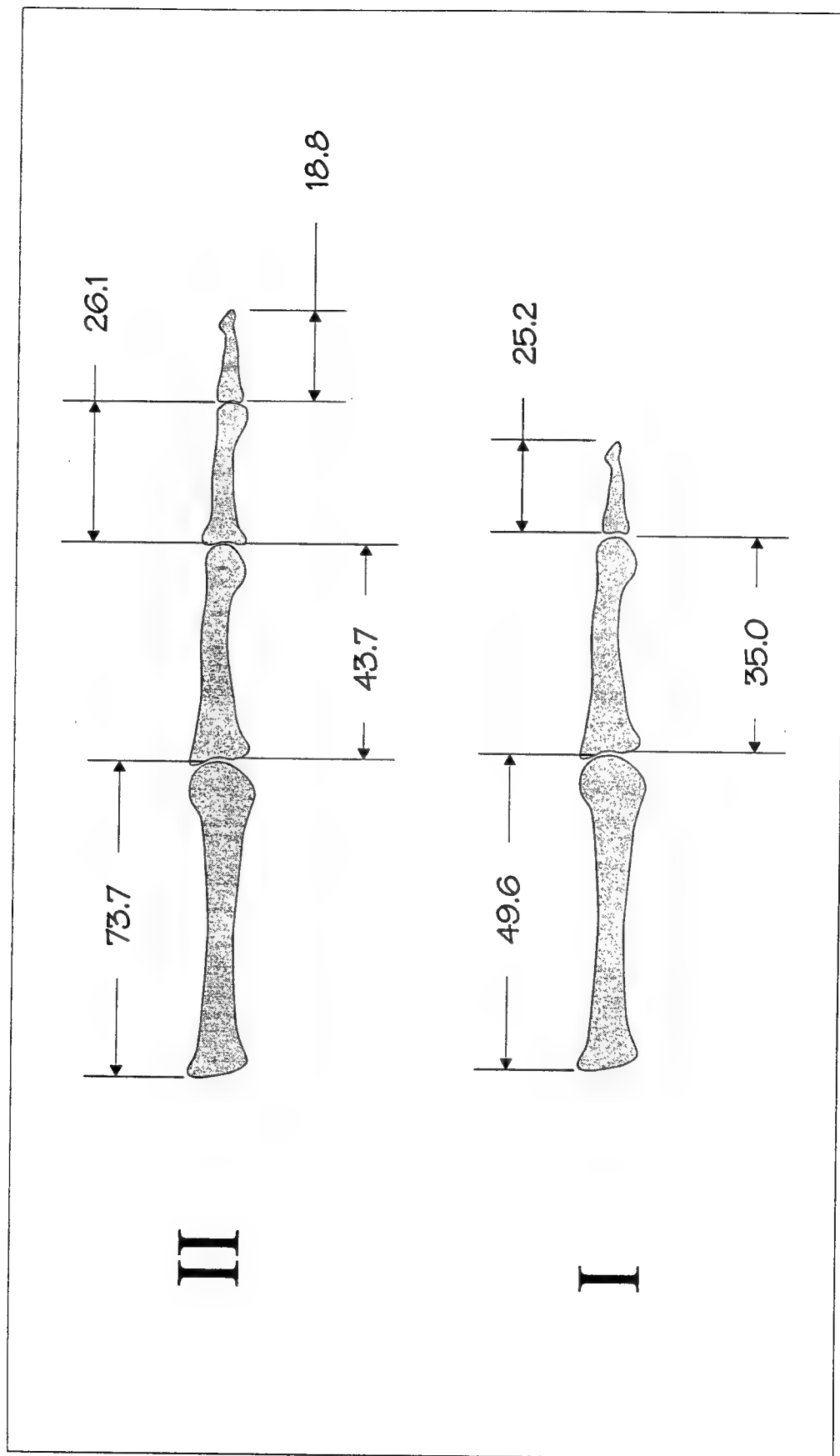




# Average Digit Lengths

## Digits I and II

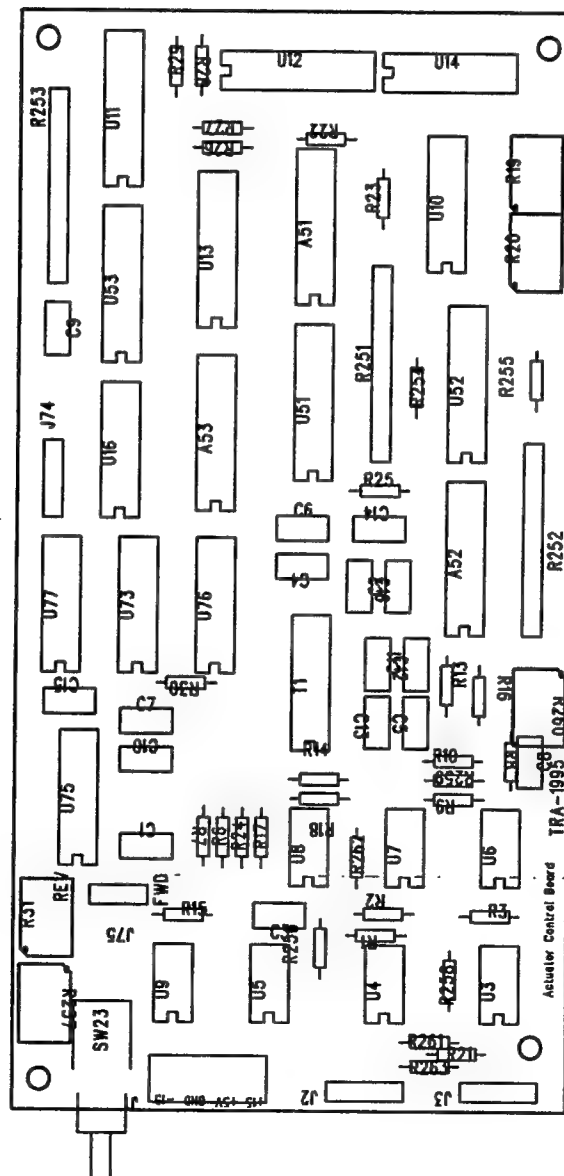
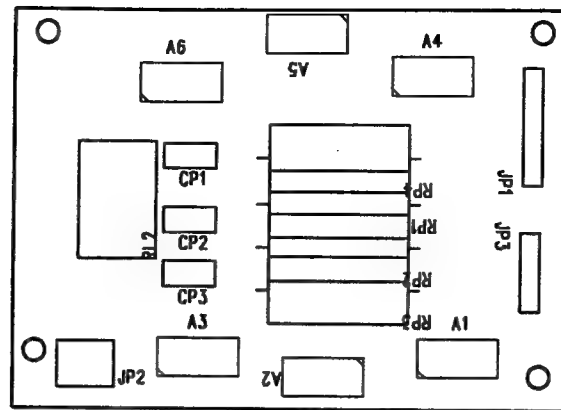
Dimensions in mm

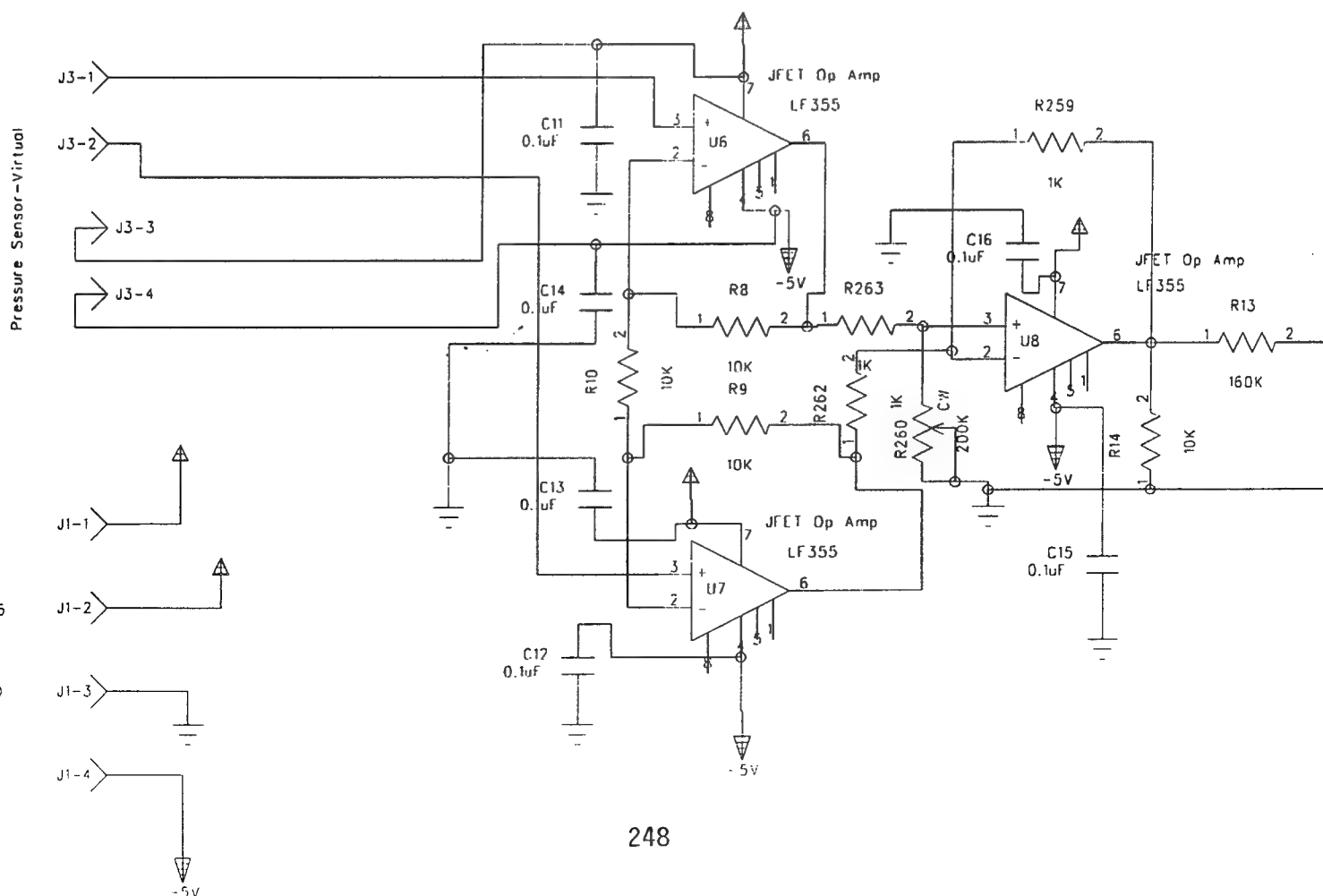
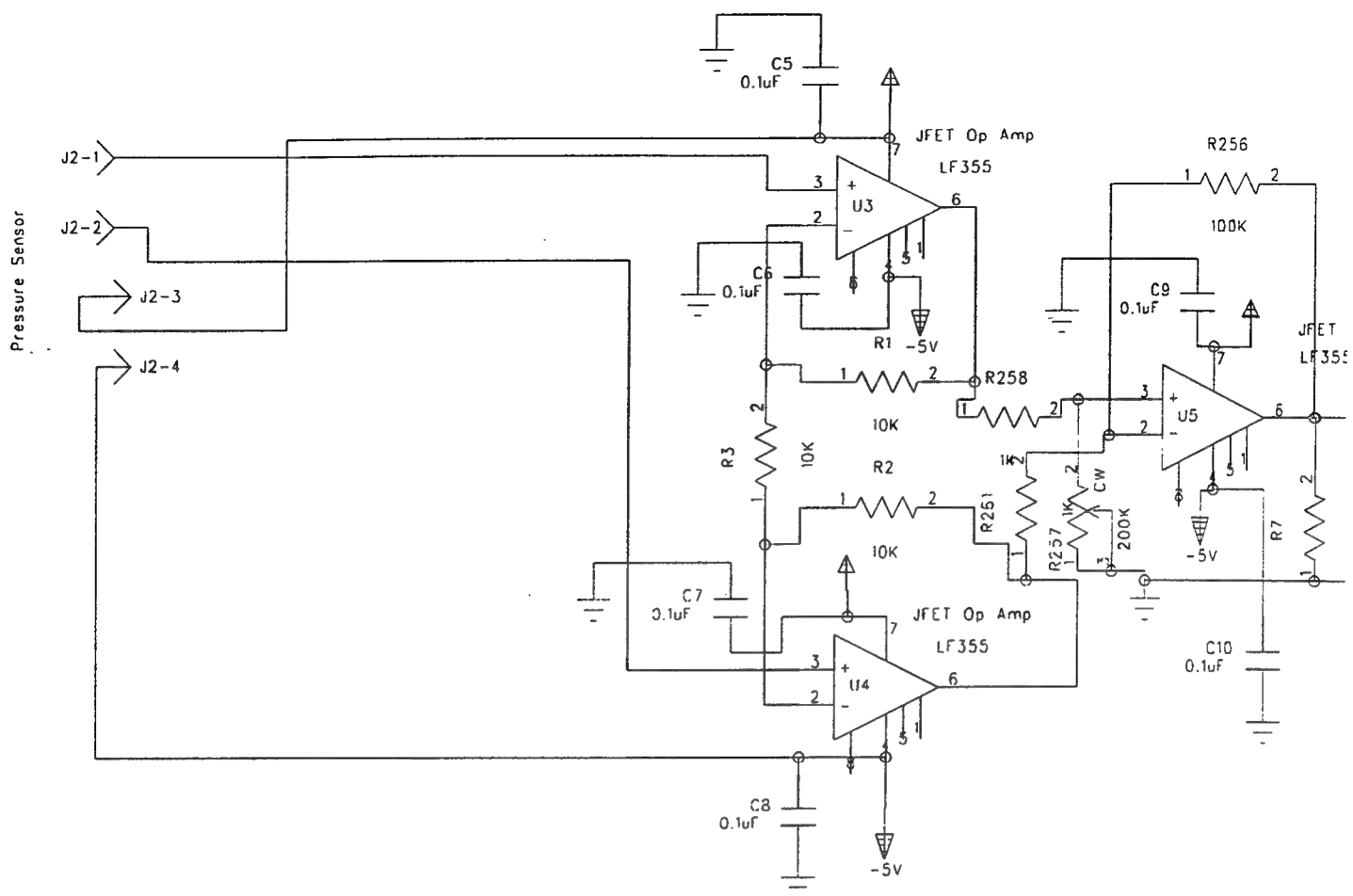


Poznanski A, "The Hand in Radiologic Diagnosis", Second Edition. W.B. Saunders Company, Philadelphia, pp 35-40, 1984.

## ♦ Appendix B ♦

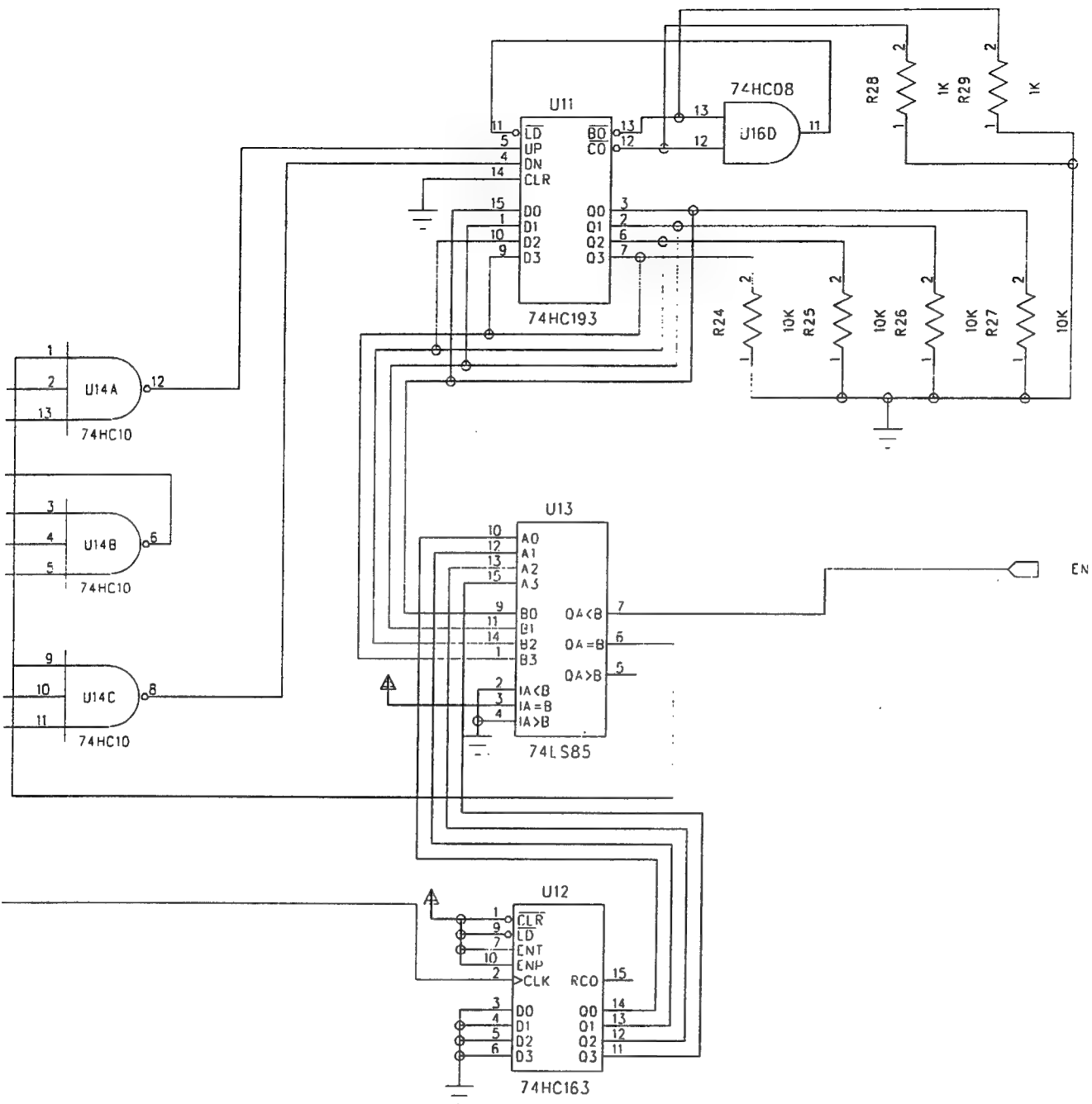
### Engineering Drawings - Electrical



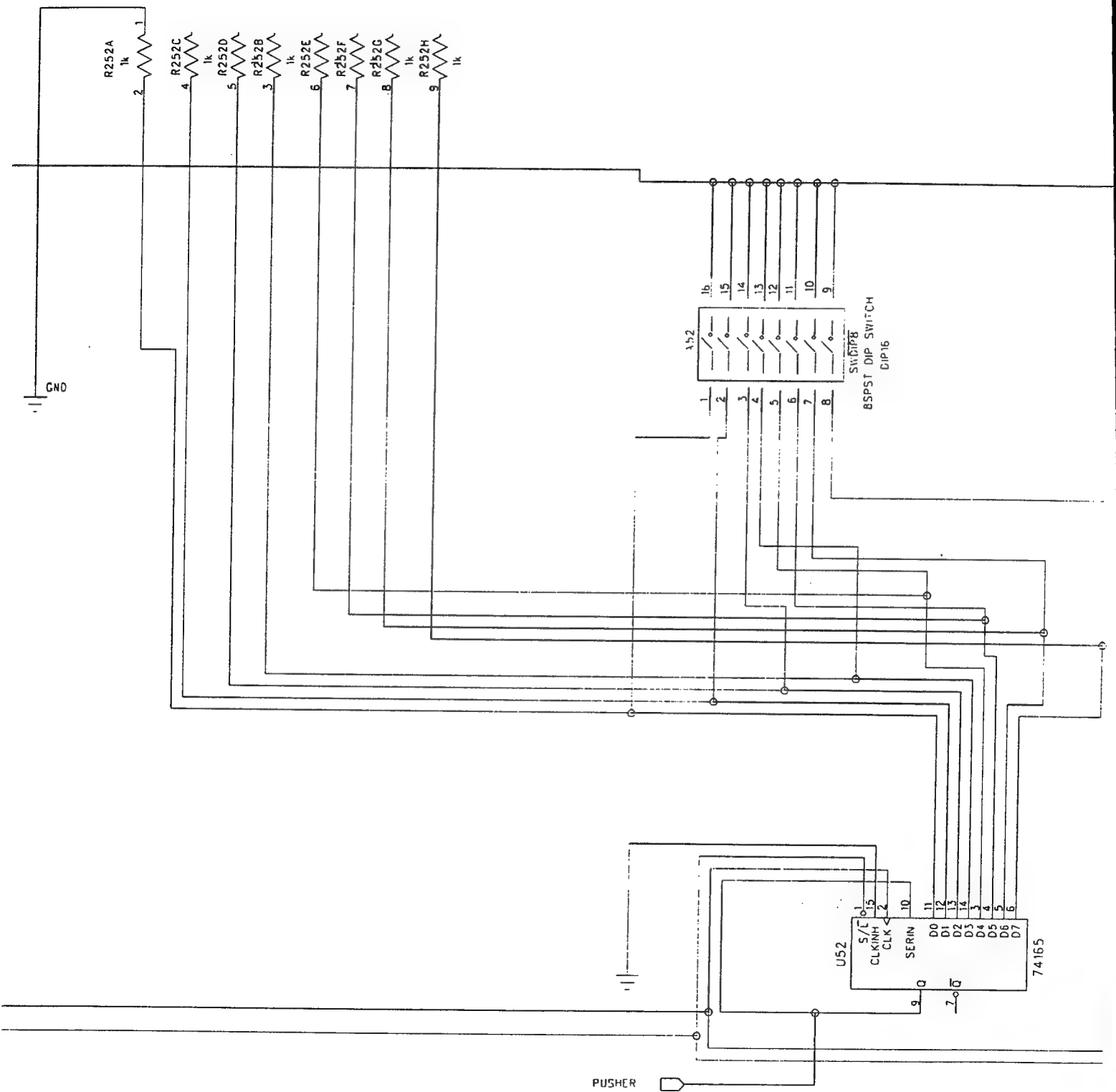




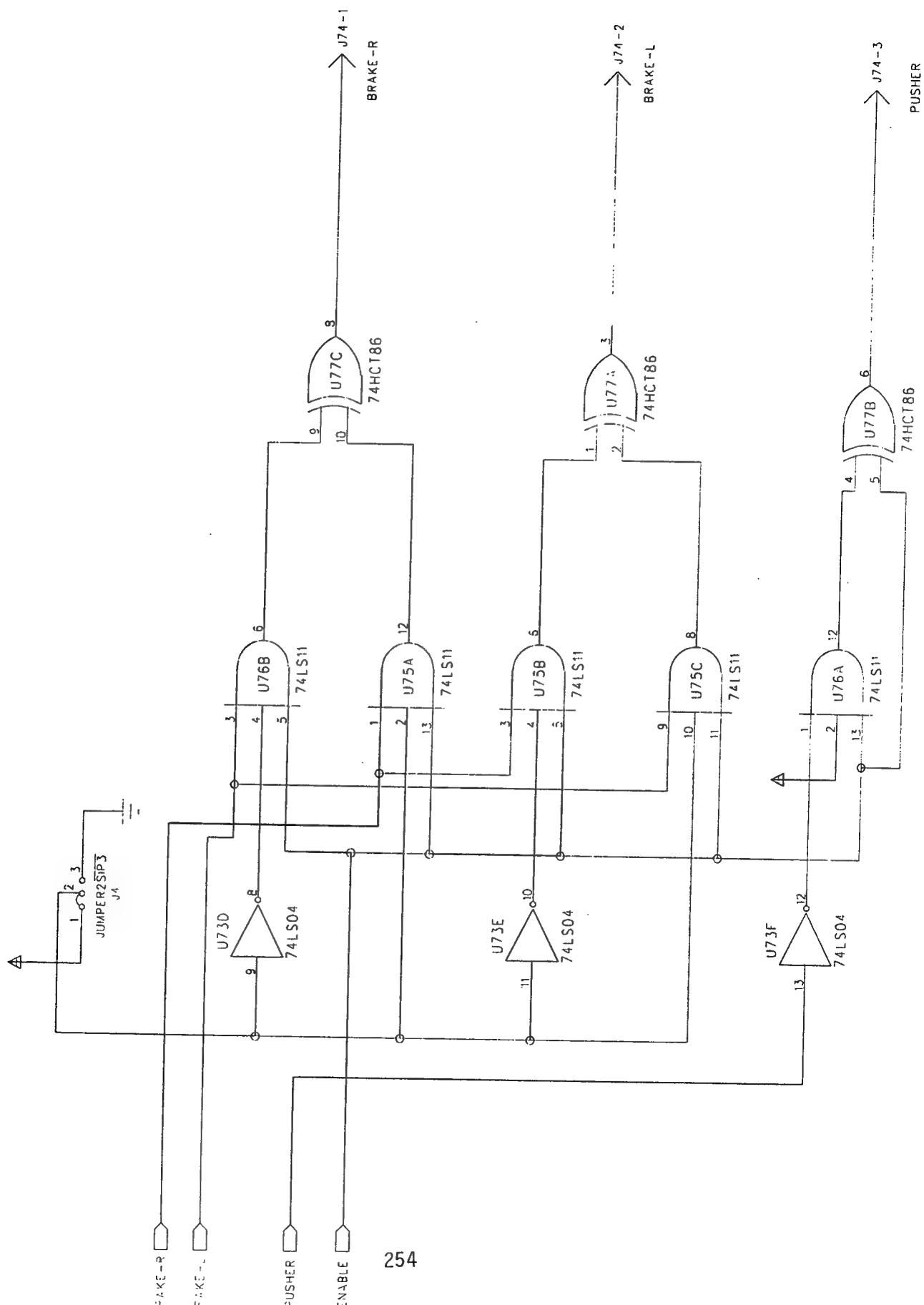












## ♦ Appendix C ♦

### Software - Computer Programs

```

/*
*This graphical interface program will allow input of position information via
*an A/D interface card (PC30D-Cyberspace Research) and output force signals to
*be used by the TRA motors. This interface is part of a closed loop system to
*simulate a force feedback exoskeleton.
*
*Program written by: Kristofer J. James
*Company written for: Technical Research Associates
*Date: September 25, 1995
*Version: 1.1
*
*Hardware requirements: 486CPU, VGA, PC30D (or similar) interface board, TRA angle *sensors, TRA motors,
and TRA designed interface electronics.
*
***** */

#include <conio.h>
#include <stdlib.h>
#include <math.h>
#include <graph.h>
#include <malloc.h>
#include <ctype.h>
#include <stddef.h>
#include "pc30.h"

#define ROTATE 0.000767

char far *buffer;      /* Buffer for image storage */
char far *xbuffer;     /* Buffer for image storage */
size_t imsize;
short square_pos[8]={400,5,410,12,420,20,430,27}; /* Position of squares for initial image capture (x,y) */
short square_size[4]={70,50,30,10}; /* Parameter for square sizes */
long sx,sy,n=4,n_flag=0; /* sx,sy indicate position of animated square; n is a counter; n_flag indicates
if the square is being animated or not */
long cross_prod[4]={0,0,0,0},col_flag=0; /* cross_prod stores the sign of the cross product for each square;
col_flag indicates if a collision with a smaller square has occurred */
long cross_product; /* cross_product is the cross product between the finger segment and the cor-
ners of the square */

main()
{
    short x[4]={210,330,410,450}; /*xa, ya:position points a=phalange */
    short xt[3]={210,310,360}; /*xta, yta:thumb position points a=phalange */
    short y[4]={120,120,120,120};
    short yt[3]={220,220,220};
    int i,int_lvl=5,quit_flag=0; /* int_lvl=interrupt level of PC30 board */
    int ang_sample[9]={1,1,1,1,1,1,1,1,1}; /* Variables to record A/D values */
    double jang[4]={0.0,1.0,1.0,1.0}; /* index joint angles */
    double jangt[4]={0.0,1.0,1.0,1.0}; /* thumb joint angles */

    char key_hit;

    x[0]=210; y[0]=120; /* X and Y offset */

```

```

xt[0]=210; yt[0]=220;          /* X and Y thumb offset */

initialize(x[0],y[0],xt[0],yt[0]);

do
{
    do
    {
        /* Index Finger */
        _setactivepage(0);
        _setvisualpage(1);
        for(i=0; i<3; i++)
        {
            phlang(i,x[i],y[i],x[i+1],y[i+1],9);
        }
        for(i=0; i<3; i++)
        {
            ad_in(i,&ang_sample[i]);
            /* Replace the line above with the appropriate command*/
            ang_sample[i]=ang_sample[i]-2047;
            jang[i+1]=jang[i]+((float)ang_sample[i])*ROTATE;
            x[i+1]=x[i]+((120/(i+1))*cos(jang[i+1]));
            y[i+1]=y[i]+((80/(i+1))*sin(jang[i+1]));
            phlang2(i,x[i],y[i],x[i+1],y[i+1],12);
            _setvisualpage(0);
        }

        /* Thumb */

        for(i=0; i<2; i++)
        {
            phlangt(i,xt[i],yt[i],xt[i+1],yt[i+1],9);
        }

        for(i=0; i<2; i++)
        {
            ad_in(i+3,&ang_sample[i+3]);
            ang_sample[i+3]=2047;
            ang_sample[i+3]=ang_sample[i+3]-2047;
            jangt[i+1]=jangt[i]+((float)ang_sample[i+3])*ROTATE;
            xt[i+1]=xt[i]+((80/(i+1))*cos(jangt[i+1]));
            yt[i+1]=yt[i]-((80/(i+1))*sin(jangt[i+1]));
            phlangt(i,xt[i],yt[i],xt[i+1],yt[i+1],13);
        }

        /*

    }while(!kbhit());
    _setactivepage(1);
    key_hit=getch();
    switch (key_hit)
    {
        case NULL:
            break;

```



```

        case 'q':
            quit_flag=1;
            break;

        case 'Q':
            quit_flag=1;
            break;

        case 27:
            quit_flag=1;
            break;

        case '0':
            if(n!=0 && n_flag!=0) break;
            n=0;
            if(n_flag!=0)
            {
                _putimage(sx,sy,buffer,_GXOR);
                n_flag=0;
                break;
            }
            sx=250;sy=200;
            _putimage(sx,sy,buffer,_GXOR);
            n_flag=1;
            break;

/*      case '1':
            if(n!=1 && n_flag!=0) break;
            n=1;
            if(n_flag!=0)
            {
                _putimage(sx,sy,buffer,_GXOR);
                n_flag=0;
                break;
            }
            sx=250;sy=200;
            _putimage(sx,sy,buffer,_GXOR);
            n_flag=1;
            break;

        case '2':
            if(n!=2 && n_flag!=0) break;
            n=2;
            if(n_flag!=0)
            {
                _putimage(sx,sy,buffer,_GXOR);
                n_flag=0;
                break;
            }
            sx=250;sy=200;
            _putimage(sx,sy,buffer,_GXOR);
            n_flag=1;
            break;

```

```

        case '3':
            if(n!=3 && n_flag!=0) break;
            n=3;
            if(n_flag!=0)
            {
                _putimage(sx,sy,buffer,_GXOR);
                n_flag=0;
                break;
            }
            sx=250;sy=200;
            _putimage(sx,sy,buffer,_GXOR);
            n_flag=1;
            break;
*/

        case 72:
            if(n_flag==1)
            {
                _putimage(sx,sy,buffer,_GXOR);
                sy=sy-5;
                if(sy<=0) sy=0;
                _putimage(sx,sy,buffer,_GXOR);
            }
            break;

        case 80:
            if(n_flag==1)
            {
                _putimage(sx,sy,buffer,_GXOR);
                sy=sy+5;
                if(sy>=295) sy=295;
                _putimage(sx,sy,buffer,_GXOR);
            }
            break;

        case 77:
            if(n_flag==1)
            {
                _putimage(sx,sy,buffer,_GXOR);
                sx=sx+5;
                if(sx>=580) sx=580;
                _putimage(sx,sy,buffer,_GXOR);
            }
            break;

        case 75:
            if(n_flag==1)
            {
                _putimage(sx,sy,buffer,_GXOR);
                sx=sx-5;
                if(sx<=165) sx=165;
                _putimage(sx,sy,buffer,_GXOR);
            }
            break;

        default:
            break;
    }

```

```

    }while(quit_flag==0);

    int _close();
    _ffree(buffer);
    _ffree(xbuffer);
    exit( !_setvideomode( _DEFAULTMODE ) );
}

initialize(int x,int y,int xt,int yt)
{
    int j=0,i=0,n=0;
    float m=0.0;
    short mode=_ERESCOLOR;
    unsigned char fill[8]={255,255,255,255,255,255,255,255};
    char dummy[10];

    while( !_setvideomode( mode ) ) /* Find a valid graphics mode */
        mode--;
    if( mode == _TEXTMONO )
        exit( 1 ); /* No graphics available */

    /* Diagnostic of PC30 interface board */

    if(diag()==0) exit(0); /* Check to make sure board is OK */
    set_type(3); /* Notifying software of PC30D board */
    for(n=0; n<8; n++) set_gain(n,1);
    j = version();
    i = j/256;
    m = (float) j - i*256;
    m = i + m/100.0;
    printf("PC-30 Driver Version %5.2f\n", m);
    printf("***Press any key to continue***\n");
    getch();
    set_base(1792); /* Sets base address of PC30 board to 700 hex */
    if (diag()==0){ printf("\aPC-30 found.\n");getch();}
    else if ((get_type() < found_30bc) || (get_type() == found_126))
        printf("\n PC-30B, PC-30C, PC-30D or PC-30PG required.");

    init(); /* Initialize PC30 interface board */
    _clearscreen(_GCLEARSCREEN);
    for(n=0; n<3; n++)
    {
        _setcolor(n+3);
        _setfillmask(fill);

        _rectangle(_GFILLINTERIOR,square_pos[2*n],square_pos[2*n+1],square_pos[2*n]+square_size[n],square_pos[2
        *n+1]+(square_size[n]*0.75));
    }
    n=0;

```

```

imsize=(size_t)_imagesize(square_pos[2*n]-1,(square_pos[2*n+1]-1),(square_pos[2*n]+square_size[n]+1),(square_pos[2*n+1]+(0.75*square_size[n])+1));
buffer=(char far *)_fmalloc(imsize);

```

```

_getimage((square_pos[2*n]-1),(square_pos[2*n+1]-1),(square_pos[2*n]+square_size[n]+1),(square_pos[2*n+1]+(0.75*square_size[n])+1),buffer);

```

```

for(n=0; n<2; n++)

```

```

{
    _setactivepage(n);
    _setbkcolor(_LIGHTBLUE);
    _clearscreen(_GCLEARSCREEN);
    _setfillmask(fill);
    _setcolor(14);
    _moveto(x,y);
    _lineto(x-150,y);
    _lineto(xt,yt);
    _lineto(x,y);
    _floodfill(x-1,y+1,14);
    imsize=(size_t)_imagesize(59,119,211,221);
    xbuffer=(char far *)_fmalloc(imsize);
    _getimage(59,119,211,221,xbuffer);
    _clearscreen(_GCLEARSCREEN);
    _putimage(x-150,y,xbuffer,_GXOR);

```

```

}

```

```

}

```

```

phlang(i,xref,yref,x1,y1,color)

```

```

{
    _setcolor(color);
    _moveto(xref,yref);
    _lineto(x1,y1);
}

```

```

phlang2(i,xref,yref,x1,y1,color)

```

```

{ long sx1=0,sy1=0,sxa,sya;
  int n2,n3;
  char on1='<',on2='-',on3='>';

```

```

    _setcolor(color);
    _moveto(xref,yref);
    _lineto(x1,y1);
    col_flag=0;

```

```

/* Cross products to check for collision--if all cross products have the same
sign, there is no collision */

```

```

for (n3=2; n3>-1; n3=n3-1)
{   sxa=sx+(n3*10);sya=sy+(n3*7.5);
    for (n2=0; n2<4; n2++)

```

```

        {
            if(n2==0) sx1=sxa,sy1=sya;
            if(n2==1) sx1=sxa+square_size[n3];
            if(n2==2) sy1=sya+(square_size[n3]*0.75);
            if(n2==3) sx1=sxa+square_size[n3],sy1=sya+(0.75*square_size[n3]);
            cross_product=((xref-x1)*(yref-sy1))-((yref-y1)*(xref-sx1));
            sx1=sxa,sy1=sya;
            cross_prod[n2]=0;
            if (cross_product<0) cross_prod[n2]=-1;
            if (cross_product>0) cross_prod[n2]=1;
        }
        _setvisualpage(1);
        if (col_flag==0 && (cross_prod[0]!=cross_prod[1] || cross_prod[1]!=cross_prod[2] ||
cross_prod[2]!=cross_prod[3]))
        {
            if(i==0)
                {
                    if (cross_prod[1]<1 && cross_prod[2]>-1 && sya<y1 && x1>sxa &&
xref<sxa+square_size[n3] && yref<sya+(0.75*square_size[n3])) collision(n3,i);
                    if (cross_prod[0]>-1 && cross_prod[3]<1 && sya<y1 &&
x1<sxa+square_size[n3] && xref>sxa && yref<sya+(0.75*square_size[n3])) collision(n3,i);
                }
            if(i==1)
                {
                    if (cross_prod[1]<1 && cross_prod[2]>-1 && sya<y1 && x1>sxa &&
xref<sxa+square_size[n3] && yref<sya+(0.75*square_size[n3])) collision(n3,i);
                    if (cross_prod[0]>-1 && cross_prod[3]<1 && sya<y1 &&
x1<sxa+square_size[n3] && xref>sxa && yref<sya+(0.75*square_size[n3])) collision(n3,i);
                }
            if(i==2)
                {
                    if (cross_prod[1]<1 && cross_prod[2]>-1 && sya<y1 && x1>sxa &&
xref<sxa+square_size[n3] && yref<sya+(0.75*square_size[n3])) collision(n3,i);
                    if (cross_prod[0]>-1 && cross_prod[3]<1 && sya<y1 &&
x1<sxa+square_size[n3] && xref>sxa && yref<sya+(0.75*square_size[n3])) collision(n3,i);
                }
        }
        else
        {
            if(col_flag==0) da_out(i,2048);
        }
    }

}

phlangt(i,xtref,ytref,xt1,yt1,color)
{
    _setcolor(color);
    _moveto(xtref,ytref);
    _lineto(xt1,yt1);
}

collision(int n3,int i)
{
    int j=0;
    da_out(i,(int)((float)(n3+1)*-102.4)+2048);
    /* Replace the line above with the appropriate command. */
    col_flag=1;
}

```

# BASAC PROGRAM TO CALCULATE COIL PARAMETERS

```

DECLARE SUB wirelength (wlen, ndia, drod, dwire, nlen)
DECLARE SUB printout ()
DECLARE SUB guagesize (guage!, dwire!, res)
CLS
SCREEN 9
***** coil program *****
***** Allen P. Hilton *****
***** June 1994 *****
pi = 3.141592654#
d = 2.0106E-08
***** variables *****
'dwire = wire diameter
'drod = rod diameter
'idcoil = ID of coil
'odcoil = OD of coil
'lcoil = length of coil
'lrod = length of terfenol rod
'nlen = number of wire diameters that fit into length of coil
'ndia = number of wire diameters that fit into dia of coil
'turns = number of turns = (n-length)(n-dia)
'n = turns density = turns/length of coil
'wlen = length of wire
'rcoil = resistance of coil
'res = resistance of wire/length of wire
'H = magnetic field (Oe)
'I = current needed to achieve H
'Required voltage across coil
'S = strain of rod
'delta = change in length of rod
'guage = wire guage
'd = const 'T = prestress (equal to zero)

***** CASE ONE *****
CLS
INPUT "Desired Magnetic Field (Oe) ", H
INPUT "Wire Guage ", guage
    CALL guagesize(guage, dwire, res)
    PRINT "OD of wire = "; dwire; "in"
INPUT "Length of Terfenol rod (in) ", lrod
    lcoil = lrod INPUT "Diameter of Terfenol rod (in) ", drod
INPUT "Max outer diameter of coil (in)", odcoil

```

# BASAC PROGRAM TO CALCULATE COIL PARAMETERS

```

DECLARE SUB wirelength (wlen, ndia, drod, dwire, nlen)
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'nlen = number of wire diameters that fit into length of coil
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'turns = number of turns = (n-length)(n-dia)
'n = turns density = turns/length of coil
'wlen = length of wire
'rcoil = resistance of coil
'res = resistance of wire/length of wire
'H = magnetic field (Oe)
'I = current needed to achieve H
'Required voltage across coil
'S = strain of rod
'delta = change in length of rod
'guage = wire guage
'd = const 'T = prestress (equal to zero)

***** CASE ONE *****
CLS
INPUT "Desired Magnetic Field (Oe) ", H
INPUT "Wire Guage ", guage
    CALL guagesize(guage, dwire, res)
    PRINT "OD of wire = "; dwire; "in"
INPUT "Length of Terfenol rod (in) ", lrod
    lcoil = lrod INPUT "Diameter of Terfenol rod (in) ", drod
INPUT "Max outer diameter of coil (in)", odcoil

```

```

' ***** number of turns
nlen = CINT(lrod / dwire)
ndia = CINT(((odcoil - (drod + .01)) / 2) / dwire)
turns = nlen * ndia

' ***** length of wire
CALL wirelength(wlen, ndia, drod, dwire, nlen)

' ***** resistance of coil
rcoil = (wlen * res) / (12 * 1000)

' ***** Current in coil to achieve mag field
n = turns / (lcoil * .0254)      '0.0254 is a conversion to meters
I = (H * 1000) / (n * 4 * pi)
voltage = I * rcoil

' ***** Strain
S = d * (H * 1000 / (4 * pi)) delta = lrod * S
'PRINT S, delta
CALL printout
DO WHILE INKEY$ = "": LOOP
END

SUB guagesize (guage, dwire, res)
SELECT CASE guage
    CASE IS = 14
        dwire = .066
        res = 2.525
    CASE IS = 15
        dwire = .0589
        res = 3.184
    CASE IS = 16
        dwire = .0526
        res = 4.015
    CASE IS = 17
        dwire = .0471
        res = 5.063
    CASE IS = 18
        dwire = .042
        res = 6.384
    CASE IS = 19
        dwire = .0375
        res = 8.051
    CASE IS = 20

```



dwire = .0336  
res = 10.15  
CASE IS = 21  
dwire = .03  
res = 12.8  
CASE IS = 22  
dwire = .0268  
res = 16.14  
CASE IS = 23  
dwire = .024  
res = 20.36  
CASE IS = 24  
dwire = .0215  
res = 25.67  
CASE IS = 25  
dwire = .0192  
res = 32.36  
CASE IS = 26  
dwire = .0171  
res = 40.81  
CASE IS = 27  
dwire = .0154  
res = 51.46  
CASE IS = 28  
dwire = .0138  
res = 64.89  
CASE IS = 29  
dwire = .0123  
res = 81.83  
CASE IS = 30  
dwire = .011  
res = 103.2  
CASE IS = 31  
dwire = .0098  
res = 130.1  
CASE IS = 32  
dwire = .0089  
res = 164.1  
CASE IS = 33  
dwire = .0079  
res = 206.9  
CASE IS = 34  
dwire = .007  
res = 260.9

```

CASE IS = 35
    dwire = .0062
    res = 329!
CASE IS = 36
    dwire = .0056
    res = 414.8
CASE IS = 37
    dwire = .005
    res = 523.1
CASE IS = 38
    dwire = .0044
    res = 659.6
CASE IS = 39
    dwire = .0038
    res = 831.7
CASE IS = 40
    dwire = .0034
    res = 1049!
CASE ELSE
    PRINT "Guage size not in database ..."
INPUT "Please input dia of wire + insulation in inches ", dwire
END SELECT
END SUB

```

```

SUB printout
    SHARED H, guage, dwire, lrod, drod, odcoil, lcoil, turns, n, wlen, rcoil
    SHARED I, voltage, S, delta
    CLS
    PRINT "Magnetic Field (H) = "; H; "Oe"
    PRINT "Wire Guage = "; guage
    PRINT "Wire Diameter (with insulation) "; dwire; "in"
    PRINT "Terfenol Rod Length = "; lrod; "in"
    PRINT "Terfenol Rod Diameter = "; drod; "in"
    PRINT "Coil OD = "; odcoil; "in"
    PRINT "Length of Coil = "; lcoil; "in"
    PRINT
    PRINT "Number of turns in Coil = "; turns
    PRINT "Turns Density = "; n; "turns/meter"
    PRINT "Length of Wire in Coil = "; wlen; "in"
    PRINT "Resistance of Coil = "; rcoil; "ohms"
    PRINT
    PRINT "Current Required for Magnetic Field = "; I; "amps"
    PRINT "Voltage Required to Achieve Current = "; voltage; "Volts"

```

```
PRINT "Strain Induced by Magnetic Field = "; (S * 1000); "ppm"  
PRINT "Change in Terfenol Rod Length = "; delta; "in"  
PRINT "New Terfenol Rod Length = "; (lrod + delta); "in"
```

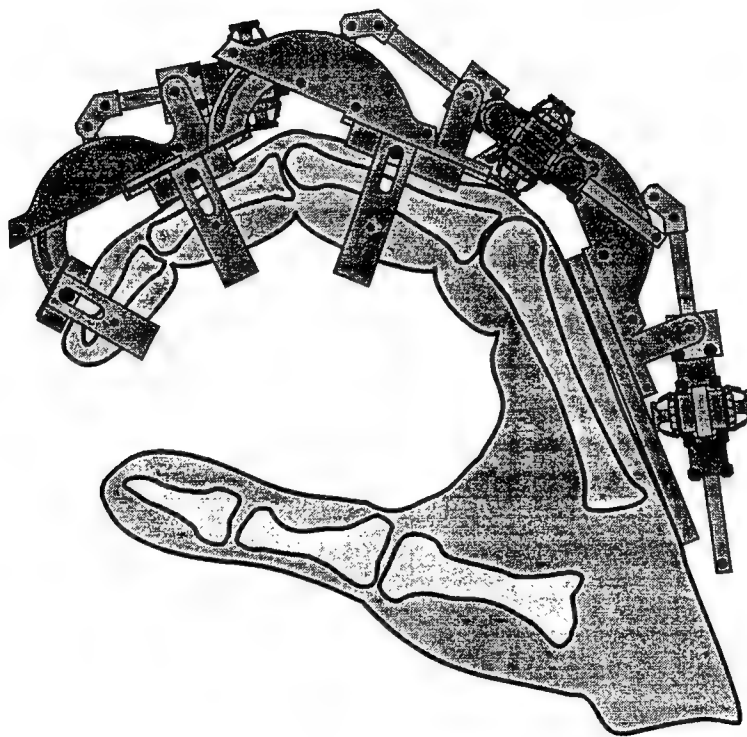
```
END SUB
```

```
SUB wirelength (wlen, ndia, drod, dwire, nlen)  
  SHARED pi  
  'wlen = 0  
  FOR j = 2 TO (ndia * 2) STEP 2  
    wlen = wlen + (((drod + .01) + (j * dwire)) * (pi * nlen))  
  NEXT j  
  PRINT wlen, ndia, drod, dwire, nlen  
END SUB
```

## ♦ Appendix D ♦

User Manual

# Terfenol-D Force Feedback Handmaster Prototype User's Manual



TECHNICAL RESEARCH ASSOCIATES, INC.  
Salt Lake City, Utah 84106

**\*\*\* NOTICE OF DISCLAIMER \*\*\***

To Whom It May Concern:

The Force Feedback Handmaster, with it's accompanying components, accessories, parts, materials, lubrications, coatings, mechanical drawings, electrical schematics, software, specifications, manuals, etc., is currently an engineering prototype. Consequently, there are no guarantees or warranties, either expressed or implied with the Force Feedback Handmaster or associated items. Furthermore, Technical Research Associates, Inc., will not be held responsible nor assume any liability for harm or injury.

This device has been designed and manufactured solely as an engineering prototype. All current instruments and associated items are for demonstration and evaluation purposes only. Sale of this device into interstate commerce is strictly prohibited until further notice.

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## **SECTION 1 - GENERAL DESCRIPTION**

---

### **GENERAL FEATURES**

The TRA Force Feedback Handmaster is a multi-dof (degree of freedom) exoskeleton hand for use in virtual reality and telerobotic environments. It combines force feedback, finger joint position sensing, and load sensing into one compact unit. This handmaster consists of five major components with unique features. They are as follows:

#### **State of the art linear motor based on Terfenol-D**

A state of the art linear motor that is based on the magnetostrictive material Terfenol-D is at the heart of the Force Feedback Handmaster. This motor is an inchworm based that consists of two brakes, a pusher, and drive shaft. It is small in size with high force and velocity. This makes it well suited to provide force feedback to the individual finger joints of the human hand.

#### **Adjustable sliding virtual joints**

The Terfenol-D based linear motors are mounted upon adjustable virtual joints that mount to the finger to track motion. The joints are made of delrin and high strength aluminum that provide a low friction contact surface. This allow the joint to move with little noticable drag.

#### **Adjustable finger rings**

The virtual joints are mounted upon adjustable finger rings that clamp onto the finger. They are adjustable for different finger sizes. The virtual joints mount in a dovetail track that permit the joints/rings to be positioned to fit a variety of finger sizes, and locked in place.

#### **Novel angular position sensors**

The virtual joints have an embedded novel angular position sensor. This sensor tracks the angular position of the joint over its full range of motion. This angular position sensor is based on the amount of light that passes through rotating polarizing films.

#### **Load cells for force measurement**

Embedded in the base of each adjustable finger ring is a load cell that measures the forces experienced by the Force Feedback Handmaster. This is a valuable component in the contol loop. It indicates the amount of force being applied by the linear motors to the fingers.



A schematic of the Force Feedback Handmaster system is illustrated below. Two power supplies are connected to the the electronic control case. The controller and power boards are securely mounted in the control case.

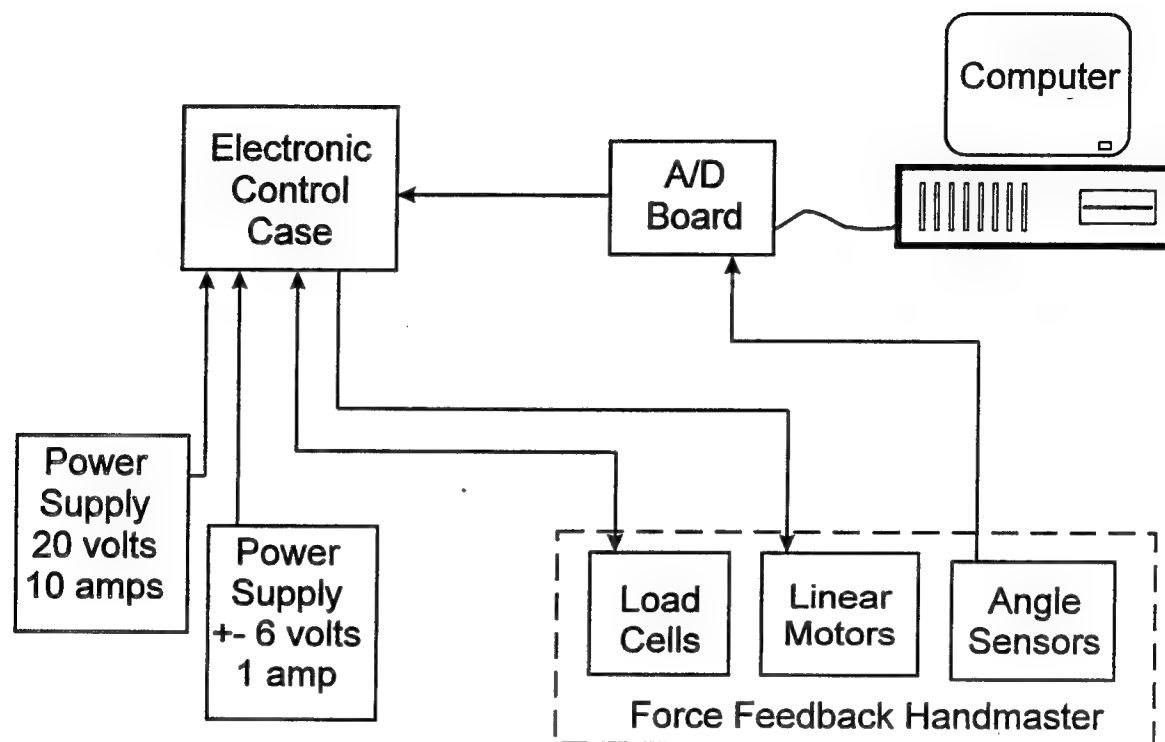


Figure 1: Schematic of Force Feedback Handmaster

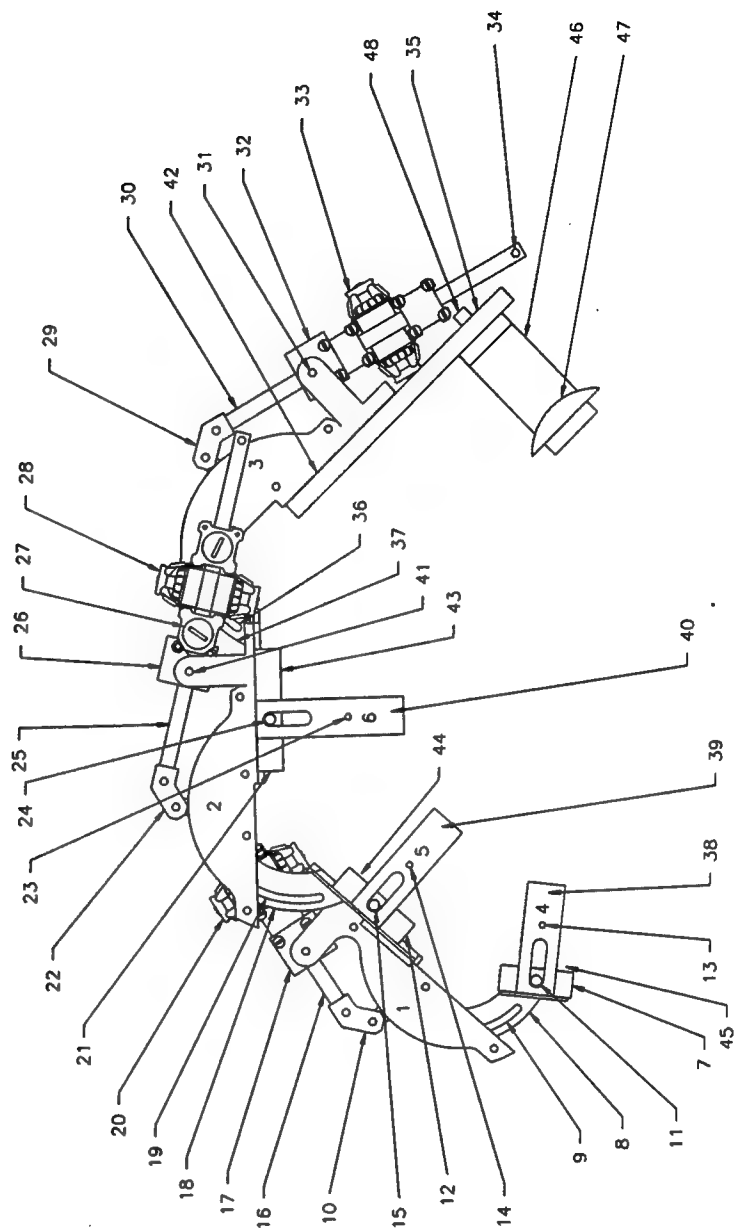
The electronic control case is connected to the load cells, the linear motors, the angle sensors, and the computer A/D board.

The computer, A/D board, and power supplies are not included with the system.

Figure 2 is a detailed labeled sketch indicating part names and locations.

# Terfenol-D Force Feedback Handmaster

- 1 DIP (Virtual Distal Interphalangeal Joint)
- 2 PIP (Virtual Proximal Interphalangeal Joint)
- 3 MIP (Virtual Metacarpophalangeal Joint)
- 4 Distal Adjustable Finger Ring
- 5 Proximal Adjustable Finger Ring
- 6 Metacarpal Adjustable Finger Ring
- 7 Distal Finger Pad
- 8 Distal Joint Shaft
- 9 Angle Sensor Polarizing Film
- 10 Drive Shaft Clevis
- 11 Finger Height Adjustment Screw
- 12 Proximal Finger Pad
- 13 Load Cell Wire Feedthru
- 14 Load Cell Wire Feedthru
- 15 Finger Height Adjustment Screw
- 16 Drive Shaft
- 17 Motor Mount
- 18 Proximal Joint Shaft
- 19 Angle Sensor Polarizing Film
- 20 Linear Motor
- 21 Metacarpal Finger Pad
- 22 Drive Shaft Clevis
- 23 Load Cell Wire Feedthru
- 24 Finger Height Adjustment Screw
- 25 Drive Shaft
- 26 Motor Mount
- 27 Brake Pad Pressure Adjustment Cap
- 28 Linear Motor
- 29 Drive Shaft Clevis
- 30 Drive Shaft
- 31 Motor Mount Pin
- 32 Motor Mount
- 33 Linear Motor
- 34 Travel Stop
- 35 Metacarpal Segment
- 36 Angle Sensor Polarizing Film
- 37 MIP Joint Shaft
- 38 Location for Embedded Load Cell
- 39 Location for Embedded Load Cell
- 40 Location for Embedded Load Cell
- 41 Motor Mount Pin
- 42 Rotating Metacarpal Joint
- 43 MIP Finger Pad
- 44 Location for Set Screw to Lock the Virtual Joint to the Ring
- 45 Location for Set Screw to Lock the Virtual Joint to the Ring
- 46 Hand Clamp
- 47 Palm Pad
- 48 Adjustment Screw for Metacarpal Segments
- 49 Travel Stop



## ***SECTION 2 - SOFTWARE***

---

### **TRA SOFTWARE: FORCE FEEDBACK SIMULATION**

The software is designed to read a signal from a TRA angle sensor and display a three segment finger. The angles between the adjacent segments will mimic the angle read by the TRA angle sensor. The TRA angle sensor outputs a voltage that is a function of its angular position. These signals are read by an analog-to-digital interface board and inputted into the software.

The screen will also display a square, movable object on the screen. The software will register any collision between the finger segments and the square. If contact is detected the system will output a virtual force signal (via a digital-to-analog interface board) to the TRA electronic control board. The level of the output signal will be determined by the depth the finger segment penetrates the square.

### **CONTROL KEYS FOR SOFTWARE:**

Up Arrow: Moves the virtual object towards the top.

Down Arrow: Moves the virtual object towards the bottom.

Left Arrow: Moves the virtual object towards the left.

Right Arrow: Moves the virtual object towards the right.

0 (Zero): Activates/Deactivates the virtual object.

Esc or 'q': Quits the program.

### **USING DIFFERENT DATA ACQUISITION BOARDS:**

There are two commands used in this program to read data from input A/D lines and produce signals from output D/A lines. These are **adin** and **daout** respectively. When using boards other than the PC-30D, these lines of code must be replaced with the command specific to the board used. The header file provided by the data interface board manufacturer will also have to replace the **#include "pc30.h"** in the program. The rest of the code is designed to run on reasonable equipped computer system.

## ***SECTION 3 - BOARD ADJUSTMENTS***

---

### **TRA CONTROLLER BOARD ADJUSTMENTS:**

The controller boards are designed to be adjustable of several key functions. The DIP switches (A51, A52, A53) are used to control the phase timing between the brakes and the pusher. These have been set for maximum efficiency for the TRA motors.

Potentiometers R257 and R260 are used to adjust the CMRR (Common Mode Rejection Ratio) of the instrumentation amplifier circuits. Connect the inputs of an input channel (e.g. J2) to a load cell (with no load being placed on the transducer) and using an oscilloscope, monitor the voltage at R7 (the pin not connected to ground). Adjust R257 until the voltage reads approximately zero volts. Repeat with the second channel monitoring the voltage at R14 (again the pin not connected to ground) and adjust R260. Potentiometer R31 adjust the main timing sequence (i.e. how much time for a full motor step) for the brakes and pusher. This has been set for maximum efficiency for the TRA motors. The threshold for the high/low current range is set by potentiometer R20. Adjusting this determines the force level which causes the relay to activate, allowing more current to flow to the pusher coil, hence increasing the force applied by the motor. The final adjustment, using R19, is the offset on the amplified load cell signal before comparing it to the virtual force signal.

## **SECTION 4 - HANDMASTER ADJUSTMENTS**

### **THE MOTOR**

The only thing to be adjusted on the Terfenol-D based linear motor is the brake pad pressure. The drive shaft is sandwiched between the brake pad and the flexure controlling the preload to the Terfenol-D in the brake. The adjustment can be seen in Figure 3 below.

Care and judgement must be used in adjusting this pressure since this same adjustment controls the preload to the Terfenol-D rod. By design, when the preload is 1000 psi, the pressure on the brake pad is at it's correct setting. If too much preload is applied and the motor is then energized, the Terfenol-D rod will fracture and will no longer function properly.

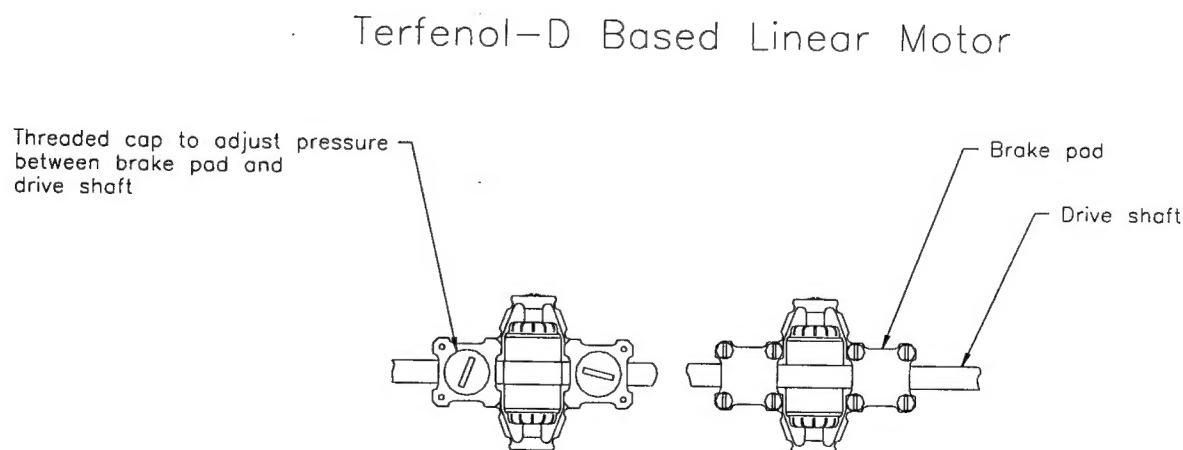


Figure 3: Adjustments on Terfenol-D based linear motor

## VIRTUAL JOINT AND ADJUSTABLE FINGER RINGS

There are two adjustments that can be made to the virtual joint and finger rings. Both are on the finger rings and can be seen in Figure 4.

The virtual joint fits into a dovetail slot on top of the finger ring. It can be positioned by sliding it into the desired position and then locking it into place with the set screw located underneath the finger pad. This adjustment can be made without removing the ring and allows for different finger lengths.

The finger ring is adjustable to allow for different finger sizes. The top portion of the ring slides up and down in the adjustment slot and can be locked into place with the adjustment screw located on the side of the ring.

Adjustable Joint Mount

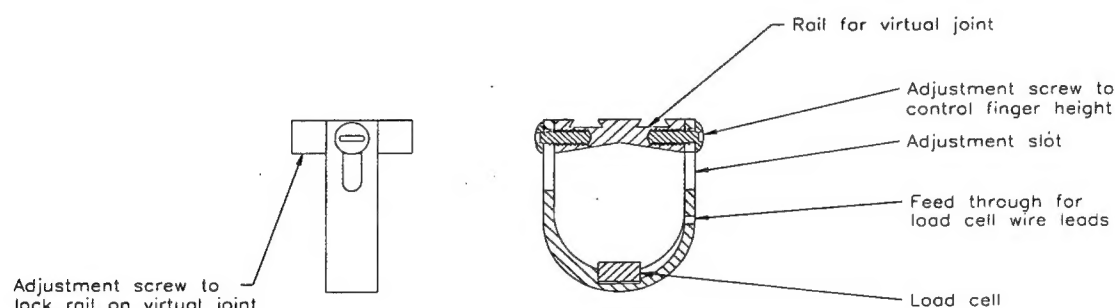


Figure 4: Adjustable Finger Joint Ring.

## HAND MOUNT

The Force Feedback Handmaster clamps onto the hand and has two adjustments. The first controls the clamping thickness across the hand. This is adjusted by loosening the bolt/nut on the left side (assuming that the hand master is mounted upon the left hand) and adjusting the straps that go around the thumb and hand until the device feels comfortable.

The other adjustment is with the segments that correspond to the metacarpal bones of the hand. These need to be positioned such that the distal end is approximately over the MIP joint COR. This is accomplished by loosening the screw on the proximal end and sliding it into position.

## DONNING THE HANDMASTER

It should be noted that the position of the virtual joint COR (center of rotation) relative to the actual COR of the finger is crucial. If the two COR's are not relatively close together, a torque is introduced inside the virtual joint and it significantly increases the friction of the joint. A suggested procedure for mounting the joints are as follows:

1. Place the finger into the adjustable finger rings and grossly position the joints.
2. Position the adjustable finger rings in approximately the middle of the finger segments and adjust them so that they clamp comfortably onto the finger segments.
3. Position the PIP virtual joint first by bending the finger approximately 90° and positioning the virtual joint's COR over where you think the actual finger COR is.
4. Lock the virtual joint to the finger rings and flex the finger to verify the adjustment.
5. If the COR's are not positioned correctly, unlock the virtual joints and try again. (Minor positioning adjustments may be made to the finger rings and the virtual joints until the most comfortable position is located.)
6. Repeat steps 3-5 with the DIP and MIP joints.
7. Connect the straps around the thumb and tighten them until it feels comfortable.
8. Adjust the position of the segments that correspond to the metacarpal bones such that the distal ends are approximately over the MIP joint COR.

## **SECTION 5 - TROUBLESHOOTING**

### MOTORS RUNNING, BUT JOINTS NOT MOVING

The most probable problem is that the drive shaft (ribbon) is loose and needs to be tightened. The drive shaft is sandwiched between the brake pad and the flexure controlling the preload to the Terfenol-D in the brake. The adjustment can be seen in Figure 3.

Care and judgement must be used in adjusting this pressure since this same adjustment controls the preload to the Terfenol-D rod. By design, when the preload is 1000 psi, the pressure on the brake pad is at it's correct setting. If too much preload is applied and the motor is then energized, the Terfenol-D rod will fracture and will no longer function properly.

Another thing to check is the cleanliness of the drive shaft (ribbon). If it is dirty, or has dirt collected under the brake pad, then the motor will not function properly. If this is the problem, then remove the brake pads and carefully clean the underlying surfaces. Before replacing the brake pads, it is a good idea to lightly coat the drive shaft (ribbon) with a light weight lubricating oil.

## **JOINTS FEEL *STICKY* AND HARD TO MOVE**

The problem is probably that the virtual joint COR (center of rotation) is not aligned with the actual finger joint COR. When this happens a torque is generated within the virtual joint and the friction force dramatically increases.

## **SECTION 6 - PRECAUTIONS**

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### **OVER-TIGHTENING OF THE THREADED CAPS**

The only thing to be adjusted on the Terfenol-D based linear motor is the brake pad pressure. The drive shaft is sandwiched between the brake pad and the flexure controlling the preload to the Terfenol-D in the brake. The adjustment can be seen in Figure 3.

Care and judgement must be used in adjusting this pressure since this same adjustment controls the preload to the Terfenol-D rod. By design, when the preload is 1000 psi, the pressure on the brake pad is at it's correct setting. If too much preload is applied and the motor is then energized, the Terfenol-D rod will fracture and will no longer function properly.

### **OVERLOADING THE LOAD CELLS**

The load cells are rated at 10 lbs and can be damaged if excessive loads are applied.

## **SECTION 7 - MAINTENANCE**

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1. Clean the polarizing film on the angle sensors with a lens free lens cloth.
2. Periodically place a small amount of light weight lubricating oil on drive shaft (ribbon).